MICROPALEONTOLOGY AND SEQUENCE STRATIGRAPHY OF MIDDLE JURASSIC D4-D5 MEMBERS OF DHRUMA FORMATION, CENTRAL SAUDI ARABIA

BY

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Dedication

This work is dedicated to ALLAH Almighty who gave me strength, courage and ability to perform all the tasks and to myself because I am the one who suffered alone.

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In the name of ALLAH, the most Gracious and most Merciful

First of all, I want to thank ALLAH almighty who give me the courage and strength and provide me with the opportunity to study in one of the prestigious universities of the world. I would also like to thanks my parents, my father Zulfiqar Ahmed Malik and my mother whose prayers led me reach to the position I am at right now.

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ABSTRACT

Full Name : [Muhammad Hammad Malik]

Thesis Title : [Micropaleontology and Sequence Stratigraphy of Middle Jurassic D4-D5 Members of Dhruma Formation, Central Saudi Arabia]

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The Dhruma Formation of Saudi Arabia belongs to the famous Jurassic Shaqra group. The formation is present in the lower part of the group and is of Bajocian to Bathonian in age (Middle Jurassic). In this master thesis, the D4 & D5 members of the Dhruma Formation are studied for sedimentology, micropaleontology and sequence stratigraphy. The outcrop selected for this study is located outside of Riyadh on Saudi White Cement Factory road. The outcrop was studied, sampled and its stratigraphic column was made in the field.

Samples taken from the outcrop were cut into slabs and thin sections for sedimentology studies and were also processed using the acid disaggregation method for micropaleontology. Representative samples were also studied for geochemical analysis of XRF, XRD & SEM. The results show the presence of 10 lithofacies in the outcrop. The lithofacies range from deep water muds to shallow water oolitic grainstones. In terms of micropaleontology, 35 species belonging to 19 different genera have been identified and documented. The ranges for representative species and their biozones are also established. Three composite sequences are determined along with 2 sequence boundaries. With the help of these data, the environment of deposition of the D5 member is found to be open marine subtidal deposited in middle portion of a vast ramp.

ملخص الرسالة

الاسم الكامل: محمد حماد ملك

عنوان الرسالة: دراسة المستحثات المجهرية، و التتابع الطباقي للعضوين ض4-ض5 المنتميين للمتكون ضرما، وسط المملكة العربية السعودية

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ينتمي متكون "ضُرما" لمجموعة "شقراء" ذات العمر الجوراسي حيث يحتل المتكون الجزء السفلي من المجموعة امتدادا من الباجوسي وحتى الباثوني (الجوراسي المتوسط). تهدف هذه الدراسة للتعرف على بيئات الترسيب، المستحثات المجهرية، و التتابع الطباقي لعضوين داخل المتكون: العضو ض4 والعضو ض5. يتواجد المكشف الذي تم دراسته خارج الرياض على طريق مصنع الأسمنت الأبيض. بعد الدراسة الحقلية ووصف العمود الطباقي للمكشف تم أخذ عينات ممثلة للطبقات المستهدف دراستها. تم قطع جزء من العينات وتحضير المقاطع الرقيقة لدراسة بيئات الترسيب القديمة في حين تم أخذ جزء آخر من العينات و معالجتها باستخدام الحمض لدراسة المستحثات المجهرية. وتم التحليل المعدني والكيمائي للعينات باستخدام جهاز حيود الأشعة السينية، جهاز فلورة الأشعة السينية والميكروسكوب الالكتروني. تشير النتائج إلى وجود 10 سحنات صخرية متراوحة بين بيئة عميقة وبيئة ضحلة. وتم توثيق وجود 35 نوع من المستحثات ينتمون ل18 جنس مختلف. تم تمييز ثلاثة تتابعات مركبة، فاصلين طبقيين، وسطح فيضان أقصى. باستخدام النتائج المسبقة، تم تفسير بيئة الترسيب للعضو ض5 كبحرية مفتوحة (تحت المدية) ترسب في الجزء الأوسط من المسطح المتسع.

CHAPTER 1

INTRODUCTION

1.1 Introduction

The Jurassic succession in Saudi Arabia has seven formations giving rise to the Shaqra Group. The Shaqra group is the most economically important group in Saudi Arabia. The carbonate and evaporite sequences of this group are the site of the World's biggest oilfield "The Ghawar". Along with the Arab D reservoir of the Ghawar oilfield, this group contains twelve reservoirs in total which are distributed throughout its formations (Hughes, 2006) (Figure 1.1).

The Dhruma Formation is present in the lower part of the group and is of Bajocian to Bathonian in age (Middle Jurassic). The name Dhruma was introduced by Max. Steineke in 1935 in an unpublished report and is named after the town of Dhruma NW of Riyadh (Powers et al, 1966). The formation is a carbonate in the subsurface but in the exposed areas and in the type section the lithology varies from carbonates to claystones. The facies changes to siliciclastics as we move to the outcrops towards Northern and Southern regions (Hughes, 2006).

Bramkamp and Steineke (1952) subdivided the formation into 3 units as lower, middle and upper units, while Powers et al. (1966) subdivided it into three members. These are the Dhibi member (lower), the Atash member (middle) and the Hisyan member (upper).

In BRGM reports, Vaslet et al., (1983) and Manivit et al (1985) further subdivided the formation into seven members and measured a collective thickness of 475m at its type section. The Dhruma Formation conformably overlies the cliff forming limestones of the Marat Formation in the reference section at Khashm adh Dhibi while in the subsurface in Rub al-Khali basin, lies on the Permo-Triassic successions (Powers et al., 1966). Upper contact with the Tuwaiq Mountain Formation is also conformable and is present in both surface and subsurface.

The Dhruma Formation has been studied for biostratigraphy and micropaleontology by different authors. These include Enay et al. (1987) who described ammonites. Tintant, 1987 and Almeras, 1987 described nautiloids and brachiopods respectively. Ostracods were studied by Depeche et al. (1987). Manvit, 1987 reported Nannofossils from the formation while gastropods were documented by Fisher et al. (2001) Extensive studies on foraminifera were carried out by Hughes (2004 a-c, 2006, 2008). The ammonite data provided the first calibrations to the International Geological Timescale while the micro-paleontological data required for age determination is sparse. However, the fossil groups that offer the most potential for age calibrations of the Jurassic are the foraminifera and the calcareous Nannofossils.

The Dhruma formation contains various species of foraminifera which are the main target of study. Hughes (2006) described thirteen foraminifera species from the Dhruma Formation which show moderately diverse distribution. Although some work has been done on the micropaleontology of Dhruma formation (e.g., Hughes, 2004 a-c, 2006, 2008; Dubaib, 2010) on the reservoir units in the subsurface, there has not been any substantial work carried out on the shale/marl units of Dhruma Formation in outcrops.

Sequence Stratigraphy evolved in the 1970s from seismic stratigraphy. In the beginning it was used as an important technique for regional correlation of sedimentary basins. Sequence stratigraphy facilitates the basin wide framework of transgressive-regressive developments and has a high prediction potential applicable to the search for commercial resources such as hydrocarbon source rocks and reservoirs. Different fossil assemblages are deposited in different depositional environments and at different water depths. Changes in the depositional conditions in the system tracts create biofacies barriers. By studying these assemblages, we can identify how the biofacies respond to transgressive-regressive developments and thus assign sequence boundaries. Different components of the sequence stratigraphic architecture like key horizons, system tracts, and para-sequences trends can also be recognized based on microfossils.

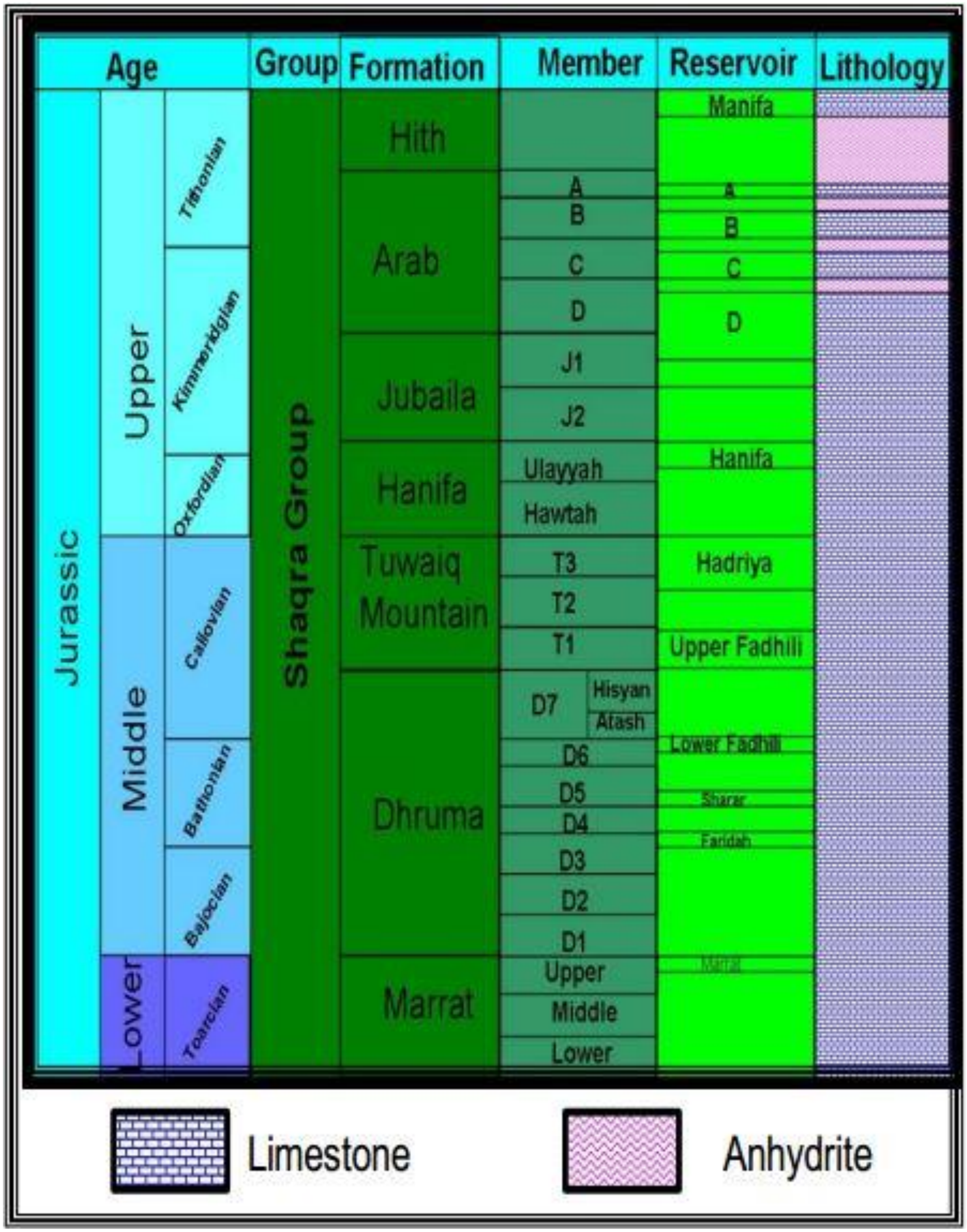


Figure 1.1: The Jurassic Shaqra Group, its formations and its reservoirs (Dubaib, 2010)

1.2 Location of Study Area

The Middle Jurassic succession is exposed in and around the vicinity of Riyadh, the Capital of Saudi Arabia. The Dhruma Formation is named after the Dhruma town which is located outside of Riyadh city and has the best exposures in the area. Nearly all 7 units of the formation are exposed west of Riyadh city making it possible to see the whole formation in one place (Figure 1.2).

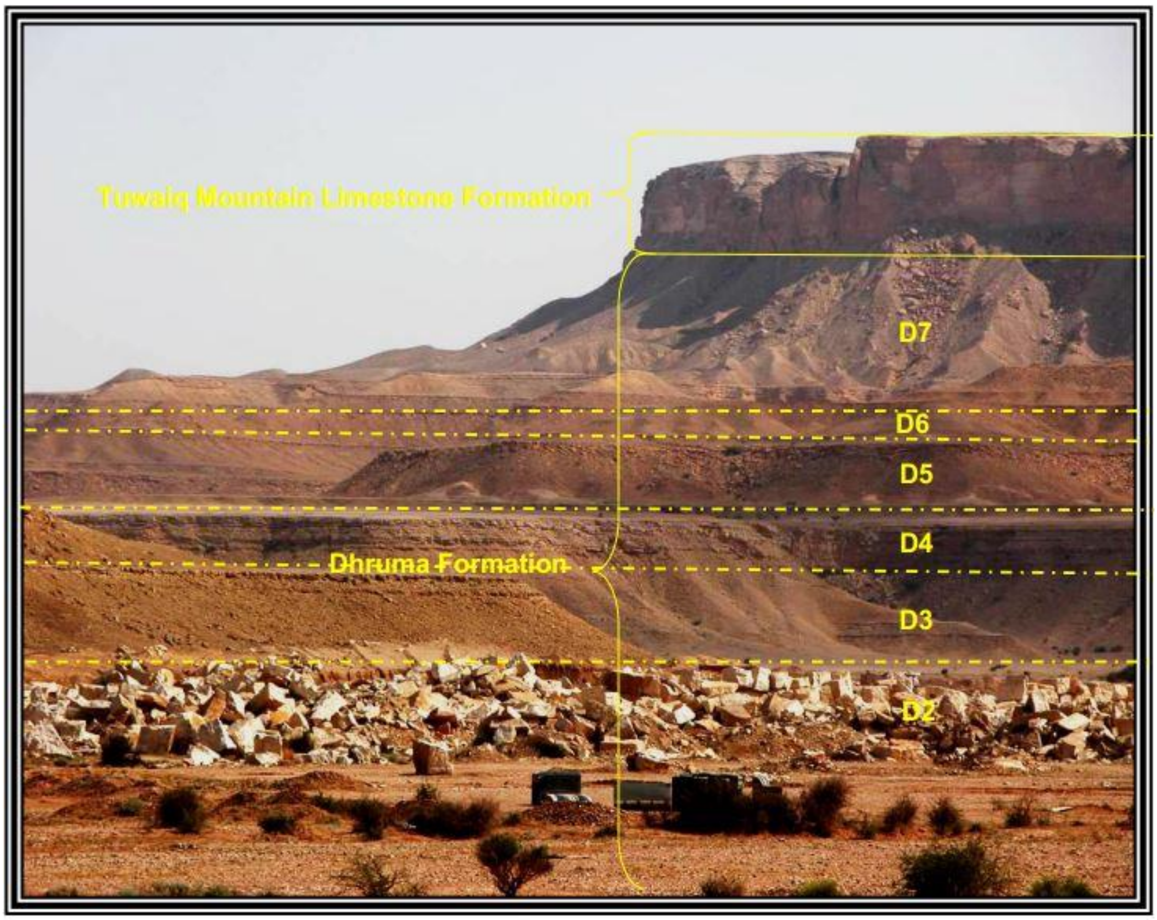


Figure 1. 2: Dhruma Formation with its units from D2 to D7. The contact of Dhruma and Tuwaiq Formation is seen at the top. (Photo courtesy of Dr. W. Hughes)

The outcrop section is located on Highway 5395. The location is approximately 35km away from the main Riyadh-Makkah Highway 40 (N24°14’33.8”; E46°15’46”). The area has good exposures of the whole Dhruma Formation from its basal units exposed in low lying areas and wadis. A fresh cut road section towards the Saudi White Cement Factory provides excellent outcrop for the study (Figure 1.3, 1.4). The section is proved to be representing the D5 (Barrah Member) of Dhruma Formation. The section is almost 70m thick and D6 member is exposed on the top of it on which cement factory facility is located.

Figure 1. 3: Outcrop location of D4 member along the road-section to Saudi White Cement Factory.

Figure 1. 4: Outcrop location of D5 member along the road-section to Saudi White Cement Factory.

1.3 Geological Setting

Seismic data and the data recovered from the deep exploration wells show us the significance of basement structures in Arabian Plate. These basement structures have provided the foundation for the development of depositional cycles and structural growth since Precambrian. Due to the presence or reactivation of these massive faults in result of tectonic episodes, geometry of the major basins within the Arabian Plate has been altered through time. Furthermore, the position of Arabian Plate through time also affects the global sea level and climatic changes. These changes along with the tectonic events results in the formation of major unconformities as a result of depositional cyclicities.

In order to understand the results based on our study, a detailed knowledge about the geological setting of the area and depositional environment of the formation is needed. To encompass this approach geologic setting of Arabian Plate is given below from Proterozoic till Jurassic.

1.3.1 Tectonic Evolution of Arabian Plate

When evolution history of any plate is dominated by tectonics rather than the eustasy, the stratigraphic record gets suffered a lot during the geological time. Tectonics act as a major influencing mechanism for governing the depositional patterns and also effecting the erosion patterns. Same has happened to the Arabian Plate throughout its evolution and deposition history. Till date the Arabian Plate is surrounded by active tectonic margins on all sides. Extension is taking place on the western and south-western margins where Red Sea Rift and Gulf of Aden are active sea floor spreading regions. Northwest is occupied by the transform movement along the Dead Sea region. Northern and eastern part of the plate is an active compressional regime with presence Bitlis and Zagros suture. South of the plate has the Makran subduction zone in the Gulf of Oman (AlSharhan and Nairn, 1997) (Figure 1.5). Presently, the western portion of the shield is occupied by igneous and metamorphic rocks of Upper Proterozoic age. These exposures were developed during and after the Pan African Orogeny during 900 to 530 million years ago (Ma) (Bell, 2004 and Be'eri-Shlevin *et al.*, 2009).

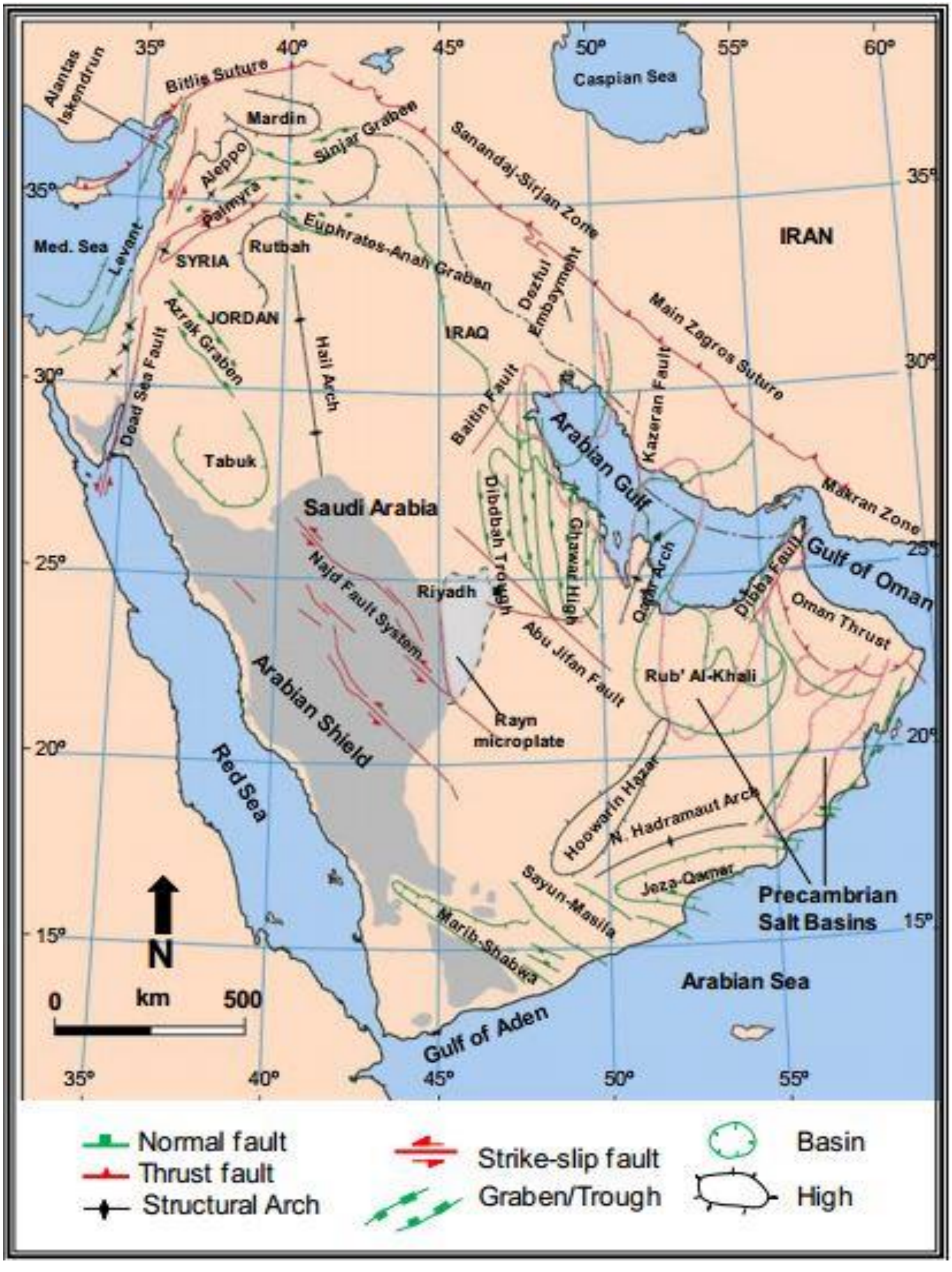


Figure 1.5: Important tectonic elements located in and around the Arabian Plate (Breton *et al.,* 2004)

The Arabian Shield remained as an active feature till Oligocene due to the active rifting taking place in the Red Sea and Gulf of Aden. This leads to a major influence of the Arabian Shield on the sedimentation occurring in the platform region of Arabian Plate (Powers *et al.,* 1996). Due to active tectonism in the area, the sedimentation and tectonics of Arabian Plate can be subdivided into four major episodes of tectonism and hiatuses. The first among them is the formation of Arabian Plate where island arcs and micro-continents were joined together to give rise to the plate during Proterozoic compression. In Paleozoic extension, second phase took place when intra-cratonic rift basins were seat of sedimentation. These basins were associated with the Najd Fault System. Third phase mark the uplifting event as a result of Hercynian Orogeny while the fourth and last phase describes the final rifting stage being taking place in Red Sea and Gulf of Aden from early Tertiary till recent (Dubaib, 2010).

1.4 Problem Statement

Due to the economic importance of Jurassic succession in Saudi Arabia and middle east, it has been studied in detail in the subsurface and surface but only for reservoir and source facies. A more encompassing approach is required to enhance our understanding of the geology, sedimentology, and biostratigraphy of the formations that host the petroleum reservoir units. The Dhruma Formation has been extensively studied by Saudi Aramco geologists (Hughes, 2008; Dubaib 2010) but their main focus remains on the reservoir facies. The shale and marl units of the formation have never been investigated for micropaleontology. This leads to the less developed high resolution sequence stratigraphy for these facies based on microfossil data. Also most of the work done is based on the data extracted from the core samples taken from the subsurface and no detailed correlation with the surface data is present. Until now only thin sections have been utilized for micro-paleontological studies. No effort is made for physical extraction of foraminifera and other microfossils by laboratory techniques which are necessary to investigate these microfossils in detail. In my work I will focus on the physical extraction of these fossils from the samples taken from outcrop. Physically extracted fossils can be studied in detail as their features are evident and can be seen in three dimensions. This helps in the accurate naming of microfossils and their habitat zones and should also help in the correlation with microfossils of other areas. Such correct information then can be used to formalize a sequence stratigraphic framework of the Middle Dhruma Formation and an exact age can also be assigned. The detailed sequence stratigraphic model based of microfossil assemblages specially foraminifera then can be utilized for demarcation of reservoir facies and horizons which can ultimately help in petroleum exploration and development. Such data can also be utilized by petroleum companied for advance techniques like directional drilling in targeted reservoir horizons.

1.5 Objectives

The main aim of the study is to conduct a detailed analysis of D5 member of the Middle Dhruma formation in terms of sedimentology, biostratigraphy, microfacies and sequence stratigraphy. The micro-paleontological data will be integrated with the sequence stratigraphic framework of the formation. This approach will provide us with integrated studies about the formation. The specific objectives of the study are itemized as follows:

- Field trips to the area for the detailed sampling and outcrop description of designated location.

- Collection of samples.
- Extraction of foraminifera and other microfossils from both limestones and marls in the laboratory for detailed micropaleontology studies.
- Thin section and geochemical studies for sedimentology.
- Formalization of full description of micro-fauna present in the samples.
- Building of depositional model based on microfacies and biofacies.
- Identification of sequences and para-sequences based on sedimentology data and field observations.
- Refining of sequences and para-sequences with help of micro-paleontological data.
- Utilization of micro-faunal distribution for foraminifera range identification and their relationship with the sequence stratigraphic framework.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The Jurassic sequence of Saudi Arabia is among the most profitable petroleum bearing sequences in the middle east as well as in the world (Hughes, 2006). It is broadly put into a single group of Formations known as the Shaqra Group. The lithostratigraphy of this group was first determined by Powers et al. (1966) and Powers (1968) and was later on modified by numerous authors in different publications e.g., Vaslet et al. (1983, 1991), Manvit et al. (1985a-b, 1986), Enay (1987), Al-Husseini (1997) and Sharland et al. (2001).

Shaqra group consists of seven formations starting from the Toarcian Marrat Formation which unconformably overlies the Minjur Formation of Triassic age. The boundary inbetween the Shaqra group and the lower Minjur Formation is marked as the Triassic/Jurassic unconformity. The Marrat Formation is dominantly composed of interbedded marine sandstones, claystones and carbonate deposits. Above the Marrat, the Dhruma formation of Bajocian to Bathonian age is present and their contact is marked by another unconformity. The Dhruma Formation is mostly carbonate in the subsurface but its lithology changes to carbonate and claystone in Central Saudi Arabia but to siliciclastics as we move towards outcrops present in the northern and southern part of the country. The Tuwaiq Mountain Formation which is of middle to late Callovian age lies above the

Dhruma formation. An unconformity is placed between these two formations. The Tuwaiq Mountain Formation mostly contains shallow-marine lagoonal and stromatoporoid carbonates. Both the Dhruma and Tuwaiq Mountain formations belong to Middle Jurassic.

Above the Tuwaiq Mountain Formation is the Upper Jurassic succession which starts from the Oxfordian Hanifa Formation. The Hanifa Formation has lower muddy carbonates which are overlain by lagoonal stromatoporoid carbonate facies in the upper part. The Jubaila limestone is composed of moderately deep marine carbonates and lies disconformably above the Hanifa formation. The upper part of Jubaila limestone consists of mostly shallow marine stromatoporoid associated assemblages. Famous Arab Formation of Kimmeridgian age overlies the Jubaila limestone and is composed of four alternating cycles of carbonate and evaporates lying above each other. The Hith Formation caps the Arab Formation and is mostly evaporite with an upper carbonate unit (Hughes, 2009). The Hith evaporite is of Tithonian age and provides a regional seal for the Jurassic reservoirs.

The Dhruma Formation was first studied by Max Stieneke (1937) whose findings are contained in an unpublished report cited by Powers et al. (1966). The formation was named after the Dhruma town located NW of Riyadh region. Type section of the Dhruma Formation is a traverse section from Khashm adh Dhibi (lat. 24 12’24’’, long. 46 07’30’’) to Khashm al Mazru’i (lat. 24 19’00N, long. 46 19’36’’ E) (Bramkamp and Steineke, 1952). This type section was composited by series of successive measurements taken from the face and back slope of Khashm adh Dhibi and Khashm al Mazur’i (Powers, 1968). Khashm adh Dhibi (24 14’ N) is the reference section of the formation (Vaslet, 1991).

2.1.1 Stratigraphy

The Dhruma Formation is best exposed in the central portion of Saudi Arabia. The formation was first studied in detail by Bramkamp and Steineke (1952) who subdivided the formation into three units; the lower, middle and upper unit respectively. The distribution was simple and they name units as lower, middle and upper units respectively. Powers et al. (1966) subdivided the Dhruma formation into 3 members and named the lower Dhruma as Dhibi limestone, the middle Dhruma as Atash and the upper Dhruma as Hisyan members respectively. They also measured the thickness of the reference section as 375m. Vaslet et al. (1983, 1985b) & Manvit et al. (1985b, 1986) through their Bureau de Recherché Geologiques et Minieres (BRGM) mapping of Mesozoic sequences on Saudi Arabia revised Powers et al., subdivisions of the formation. They subdivided the Dhruma Formation into 7 informal units and also reported a new thickness of 447m. The Lower Dhruma was divided into D1 and D2 units, middle Dhruma comprises of D3 to D6 while upper Dhruma was designated D7. Almeras (1987) suggested a new nomenclature in which he combined all the previous distributions into eight members. He named the members as Balum which is equivalent to D1, Dhibi as the D2, Jufayr as the D3, Uwaynid as the D4, Barrah as the D5, Mishraq as the D6 while the Atash and Hisyan members are equivalent to D7 unit. His changes made for the Dhruma Formation are not widely used as only names were changed and no evident lithological modifications were applied. A new member named as the Wadi ad Dawasir “delta” between the D5 and D6 members was mentioned by various authors like Enay et al. (1986; 1987), Le Nindre et al. (1987; 1990a) & Manivit et al. (1990).

The D1 unit (the Balum Member) is mainly comprised of oolitic, fossiliferous glauconitic shales at the base. This oolitic bed is overlain by laminated dolomite with stromatolitic layers which are in turn overlain by a series of interbedded shales with mudstone limestones and capped by bioclastic, ammonite rich grainstone limestone at the top (Dubaib, 2010). The D2 unit (Dhibi Member) consists of a lower succession of marls overlain by a massive cliff forming limestone. This succession is overlain by thick series of green claystone with beds of fossiliferous bioclastic nodular limestone (Powers et al., 1966).

The middle Dhruma has four units. The unit D3 (Jufayr member) starts with a 0.5m thick bed of limestone containing intraclasts of mudstone pebbles. This bed is overlain by 2m thick bioclastic limestone containing coral fragments. A thick succession of grainstone limestone with oolitic bioclastic pelloid grains overlies the lower rocks. This thick succession is capped by a thin burrowed limestone bed which can be traced to distant areas. This thin bed is overlain by 20m of grainstone limestone interbedded by bioturbated oncolitic limestone rich in echnoids (Dubaib, 2010). The D4 unit (Uwaynid Member) has well bedded mudstone limestones in the base which changes to grainstone limestone towards the top. The D5 unit (Barrah Member) contains well bedded yellow fossiliferous limestones at the base which are overlain by green marls. The upper part has bioclastic limestone with several paleo-hardground beds rich in ammonite fauna. The D6 unit (Mishraq Member) is mainly composed of interbedded claystones with mudstone limestones and bioclastic limestones (Dubaib, 2010). The Wadi ad Dawasir "delta" Member is not considered a true delta deposit due to insufficient evidence to confirm its deltaic origin and is given a Lower Bathonian age based on the fossil evidence from the upper and lower members.

The upper Dhruma has one only one unit, D7, which is subdivided into the Atash and Hisyan members. This unit is the thickest unit of the Dhruma Formation. The Atash Member named after Khashm al ’Atash is mainly tan, golden-brown chalky mudstone and packstone limestone at its base which changes to coralliferous towards the top. The Hisyan Member is named after Wadi al Hisham and is composed mainly of tan to olive-tan shales with limestone beds. Figure 1.5 shows the lithology and age of all members of Dhruma Formation.

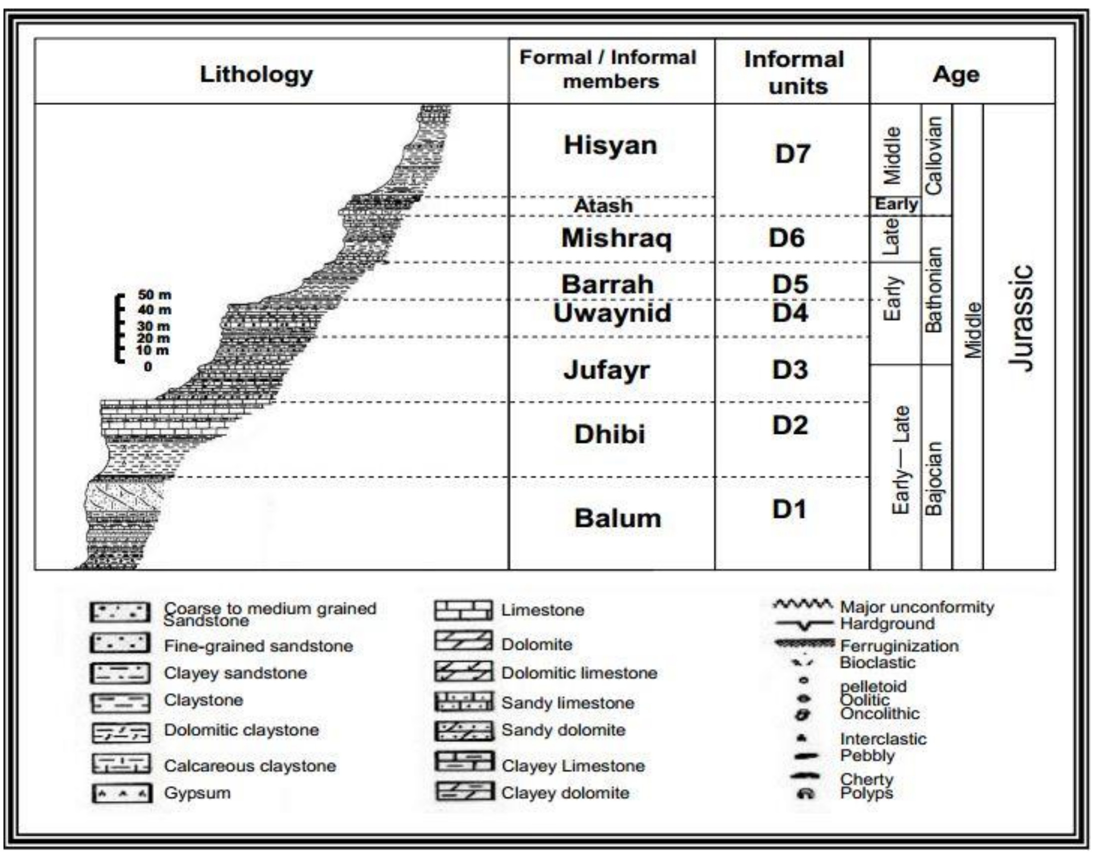


Figure 2.1: The lithology and age of all seven members of Dhruma Formation (Dubaib 2010).

2.1.2 Biostratigraphy

In terms of the biostratigraphy of the Jurassic in Saudi Arabia, the ammonites remain the only reference group. The only accepted biostratigraphic zonation of the whole Jurassic is established on the base of ammonites. The ammonite fauna of Saudi Arabia was first studied by Brankamp and Steineke (1952) who identified nine ammonite faunas. Imlay (1970) introduced eleven ammonite zones. Enay *et al*. (1987) identified seventeen ammonite faunas for the whole Jurassic and twelve in Dhruma Formation. Out of these twelve, six were in Lower Dhruma, five in the Middle Dhruma and one in the Upper Dhruma. A new ammonite zonation was later introduced by Enay and Mangold (1994) in which they correlated the ammonite species of the Arabian province with the European Sub-Mediterranean. The zonation was further modified by Enay *et al.* (2009). Figure 2.2 shows the different zonation of Jurassic Shaqra group based on ammonites.

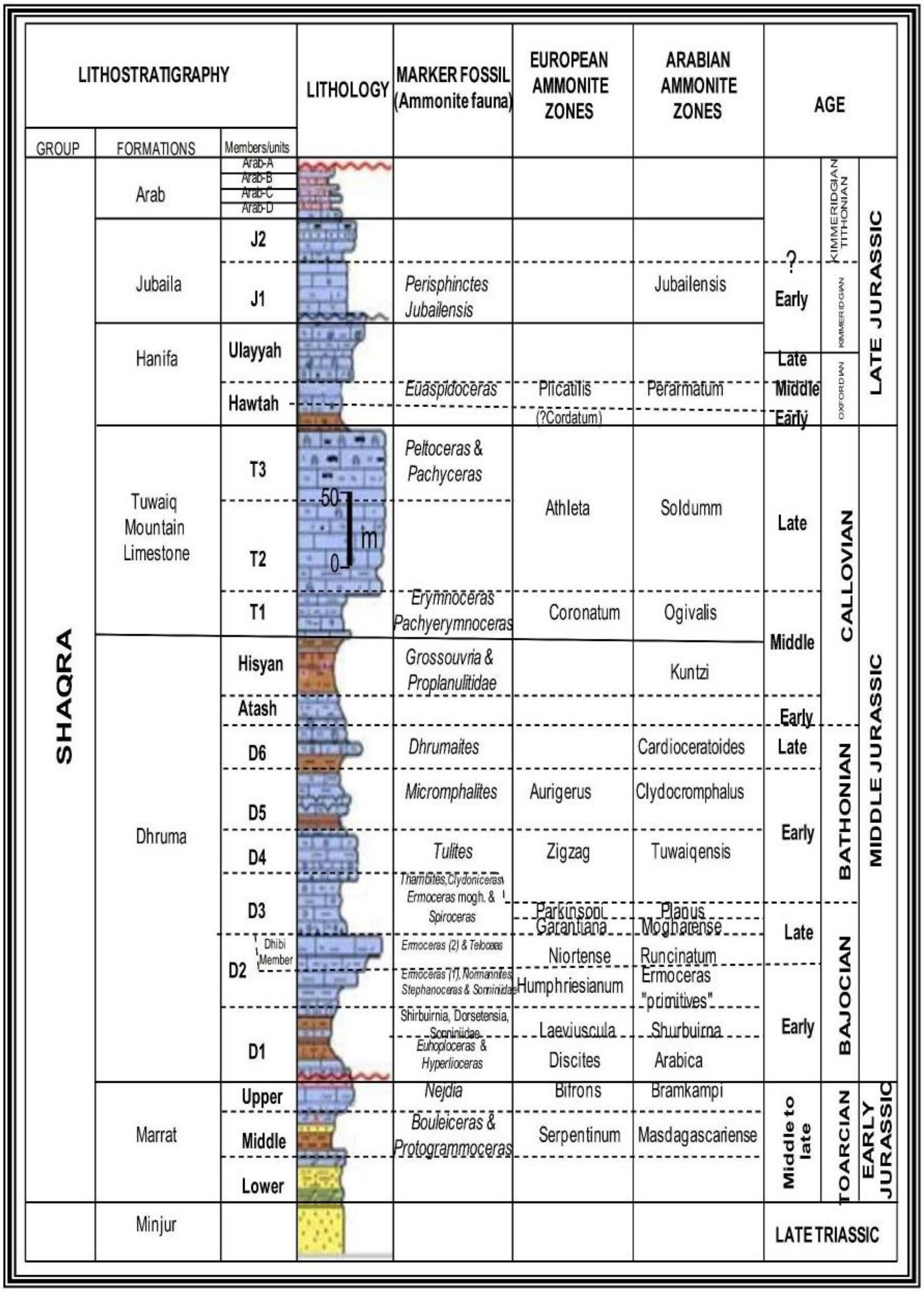


Figure 2. 2: Ammonite zones in the Formations of Jurassic Shaqra Group. (Dubaib, 2010)

Micropaleontological studies have also been carried out on the Dhruma Formation. The lower Dhruma contains calcareous nannofauna that belongs to the *Ellipsageloshaera britannica* zone of late Toarcian to Early Bathonian (Manvit, 1987). This lower part also contains the *Haurania* zone of foraminifera, which has two species *Haurania amiji* and *Haurania deserta* of late Bajocian (Powers *et al*., 1966). The Middle Dhruma has two assemblages of nannofossils which fall under *Hexalithus margharensis* zone of Middle Bajocian to Late Bathonian of Tethyan Europe (Manivit, 1987). The zone consists of *Ellipsagelosphaera communis, Hexalithus margharensis* and *Stephanolithion bigoti.* Three foraminifera zones were identified in the Middle Dhruma. The first lower zone contains *Dhrumella evoluta*, *Nautiloculina* spp., *Pfenderina* sp., *Pseudomarssonella mcclurei, P. primitiva* and *Riyadhella elongata* (Powers *et al*., 1966). The middle zone contains *Dhrumella evoluta*, *Nautiloculina* spp., *Pseudomarssonella reflexa*, *Riyadhella elongata*, *R. arabica* and *Virgulina* spp. while the upper zone has *Flabellammina* sp., *Nautiloculina* spp., *Pseudomarssonella biangulata, P. bipartita, Riyadhella inflata, R. nana, R. rotundata* (Powers *et al*., 1966). Dubaib (2010) found a Bathonian fauna in the D6 member of the Middle Dhruma and identified a foraminiferal assemblage consisting of *Redmondoides primitivus*, *R. media*, *Pseudomarssonella bipartite,* and *Siphovalvulina colomi*.

For the Upper Dhruma, the Atash and Hisyan members contain only one zone of calcareous nannofossils known as the *Stephanolithion bigoti* zone of Middle Callovian age (Manivit, 1987). The fauna of *Zeugrhabdotus erectus*, *Wautznaueria manivitae*, *Ethmolithus* cf. *gallicus*, *Polyporhabdus escaigii* and *Stephanolithion bigoti* are present in this zone. The lower Atash member was subdivided into two foraminiferal zones by Powers *et al*. (1966). The lower *Pfenderina trochoidea* Zone contains *Kurnubia variabilis*, *Nautiloculina* spp., *Pfenderella arabica*, *Pfenderina gracilis*, *P. neocomiensis* and *P. trochoidea.* The upper *Pseudocyclammina* Zone contains a foraminiferal assemblage of *Pseudomarssonella maxima*, *P. plicata, Sanderella laynei* and *Trocholina* spp. The upper Hisyan member was also subdivided into two zones. The lower *Praekurnubia crusei* Zone contains a foraminiferal assemblage of *Kurnubia* spp., *Praekurnubia crusci*, *Riyadhella hemeri* and *Trocholina* sp., and the upper *Kurnubia bramkampi* Zone contains *Conicospirillina* sp., *Kurnubia bramkampi*, *K.* spp., *Pseudomarssonella media*, *Riyadhella* sp., *Steinekella crusei*, *Trocholina palastinienses* and *T.* cf. *T. palastinienses* (Powers *et al*. 1966, 1968).

Hughes (2003) also studied foraminifera from the Jurassic formations mostly in the subsurface and was able to find some assemblages. These foraminifera species include *Ophthalmidium* spp., *"Pfenderina" trochoidea*?, *Satorina apuliensis*, *Trocholina elongata*, *Ammobaculites* spp., *Nautiloculina oolithica*, *"Pfenderina" salernitana*, *Redmondoides lugeoni*, *Redmondoides* sp. cf. *rotundata*, *Valvulina* sp., *Trochamijiella gollehstanehi*, *Parurgonia caelinensis* and *Pseudocyclammina* sp. cf. *lituus*.

2.1.3 Sequence Stratigraphy

For sequence stratigraphy, the first works date back to Vail et al. (1977), who provided the global eustatic sequence stratigraphic framework. In 1988, Haq *et al*. for the first time provided a detailed global chronostratigraphy and sea level change cycles for the Mesozoic and Cenozoic Era. Le Nindre *et al*. (1990) were the first to study the transgressive-regressive sequences of Mesozoic in Central Saudi Arabia and were followed by Vaslet *et al*. (1991). A similar approach was followed by Al-Husseini (1997) who for the first time correlated the lateral distribution of Jurassic strata for Arabian Gulf countries in terms of their sequence stratigraphy. He used biostratigraphic and stratigraphic studies as a basis for his work. His prominent correlation was about the early Jurassic hiatus, Toarcian transgression, Aalenian hiatus, Bajocian-Bathonian transgression and the Callovian-Kimeridgian sequences. Al-Husseini put the lower Dhruma Shale in a separate sequence and the upper Dhruma along with Tuwaiq Mountain Limestone in a single Callovian-Kimeridgian sequence. Sharland *et al*. (2001; 2004) did a detailed study and were able to formalize and study 63 maximum flooding surfaces throughout the Arabian plate.

In 2005, a regional chart was produced by Haq and Al-Qahtani in which they describe the regional cycle chart of sea level changes affecting the Arabian platform. Enay *et al*. (2009) recently studied the sequence stratigraphy of Middle Dhruma Formation based on biostratigraphic data. They separated the previously joined depositional package of D4 to D6 members. By studying the biostratigraphy, they were able to interpret the shales of the lower Bathonian D5 unit to be a maximum flooding surface while the upper part of D5 as regressive system tract. They separate D5 and D6 members by Wadi ad Dawasir "delta" unit of upper Lower to Middle Bathonian and also mentioned a Hiatus in late middle Bathonian. The D6 and lower part of D7 was also interpreted as transgressive system tract and shales of Hisyan member as maximum flooding surface. The sequence stratigraphy chart for the Jurassic of Saudi Arabia formulized by Enay *et al*., (2009) is shown in figure 2.3.

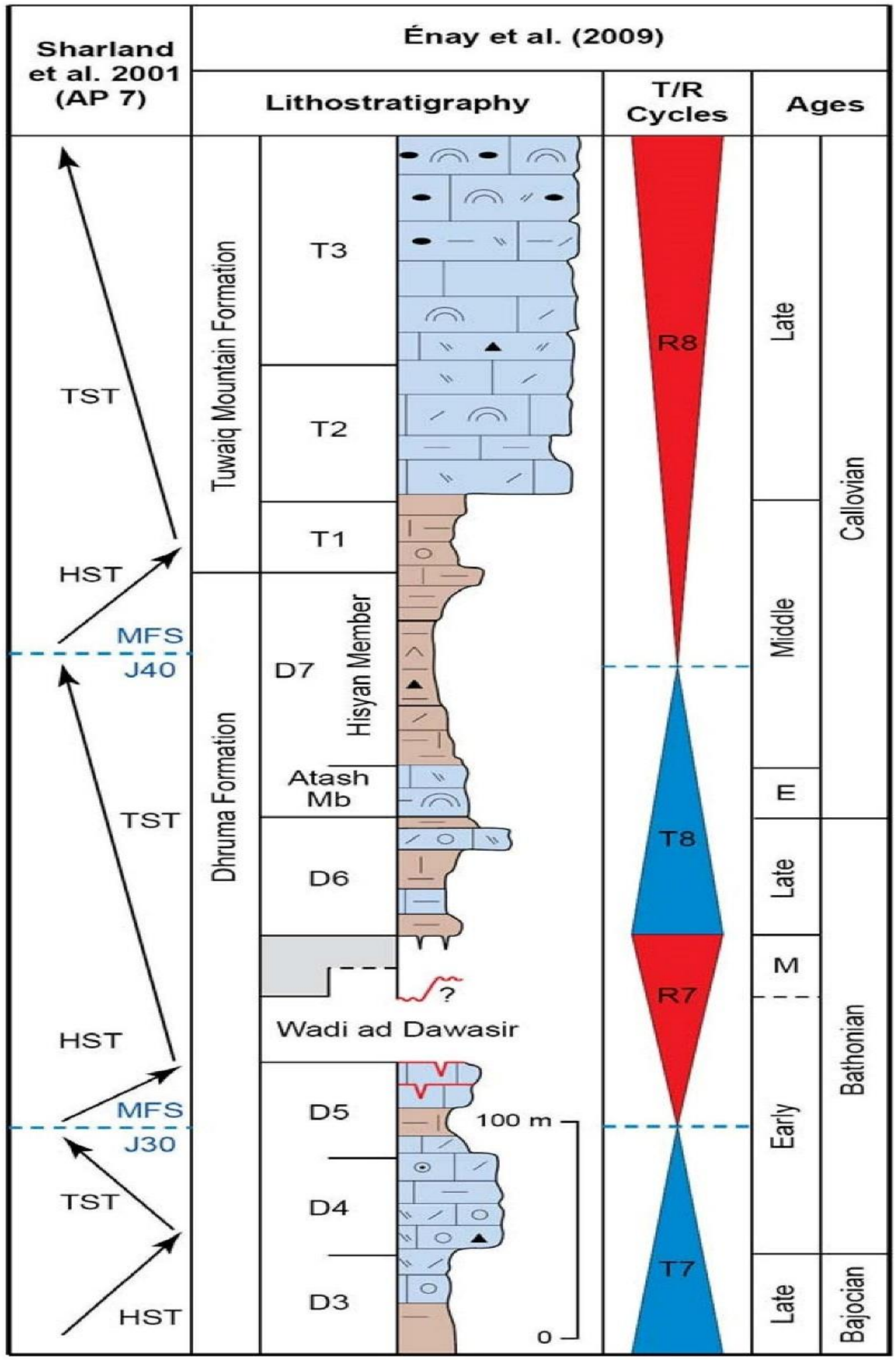


Figure 2.3: Sequence Stratigraphic interpretation of Jurassic Formations, Saudi Arabia. (Enay *et al.,* 2009)

Al-Husseini (2009) updated Triassic & Jurassic stratigraphy of Saudi Arabia for Middle East Geologic Timescale. In his work he identified 11 third order sequences in the seven formations of Jurassic Shaqra group. Out of these eleven, three are present in Dhruma Formation which are:

1. *Lower Dhruma Sequence* of Bajocian including Balum (D1) and Dhibi (D2) members. The Balum member contains MFS J20.
2. *Dhruma Sequence B* of Late Bajocian to Mid Bathonian including Uwaynid (D3), Barrah (D4), Mishraq (D5) and Wadi ad Dawasir "delta" unit. The D5 unit contains the MFS J30.

Dhruma Sequence A of Late Bathonian to Early-mid Callovian including D6 unit along with D7 and D8 members of Atash and Hisyan. The Hisyan member contains MFS J40.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The conducted study of the middle two members of the Dhruma Formation is based on two forms of data; sedimentological data and the micropaleontological data. The data extraction for both required separate techniques to be utilized. The sedimentological studies require outcrop descriptions, thin section petrographical analysis along with other essential laboratory techniques such as XRD, XRF, and SEM. Micropaleontological data on the other hand was gathered by two different laboratory methods: normal soap based disaggregation or acetic acid extraction technique, based on the nature of the sample. Both aspects of the study when combined give us a detailed knowledge about the depositional history of the formation. The generalized methodology of the work is given in Figure 3.1.

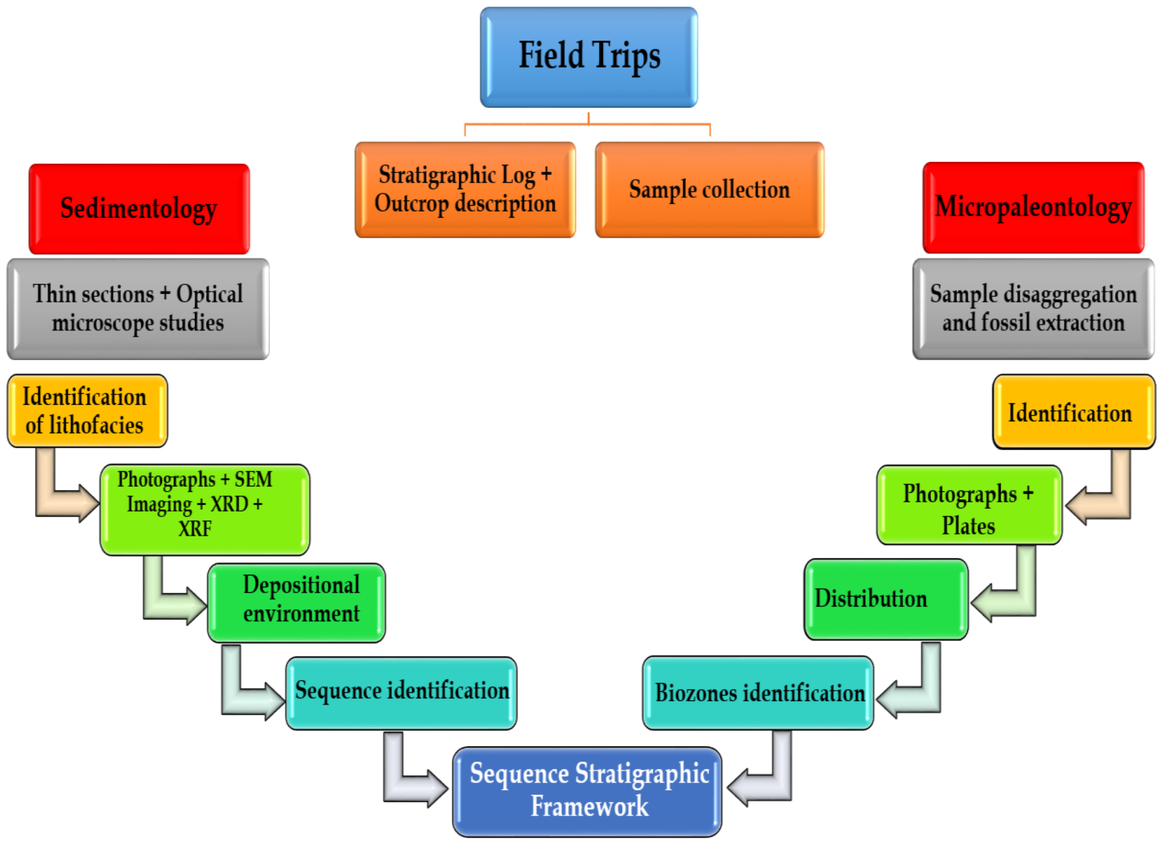


Figure 3.1: Generalized methodology flow chart for the study

3.2 Materials

The outcrop location is a road-cut section which makes it quite easy to sample the location in detail. For this study we covered nearly 70m of the outcrop exposed along the Saudi White Cement Co road which represents the D5 & D6 member. About 85 samples were collected from the outcrop, which includes samples from hard limestone layers as well as the soft muddy and marly layers. The sampling strategy of one sample per representative bed was applied, and more samples were taken from beds of greater thickness to check the heterogeneity (Figure 3.2). Out of 85 samples, 21 which were purely of mud dominated fabric were used for microfossil extraction only. The remaining grainy samples were cut, slabbed, and utilized for both sedimentology and microfossil studies.

Figure 3.2: Sampling being done on the field. Samples from every bed were taken, with additional samples from thicker beds.

3.3 Methodology Applied

3.3.1 Laboratory Studies

The samples taken from the field were cut into the slabs in laboratory. The slabs were then etched with diluted hydrochloric acid (HCl) to better expose the details of the sample, and were examined under a binocular stereoscopic microscope. The slabs provide us with better details in a broad perspective than the thin sections, and are useful for the general description of the rock fabrics. These slabs were later photographed before utilizing them for thin section preparation (Figure 3.3).

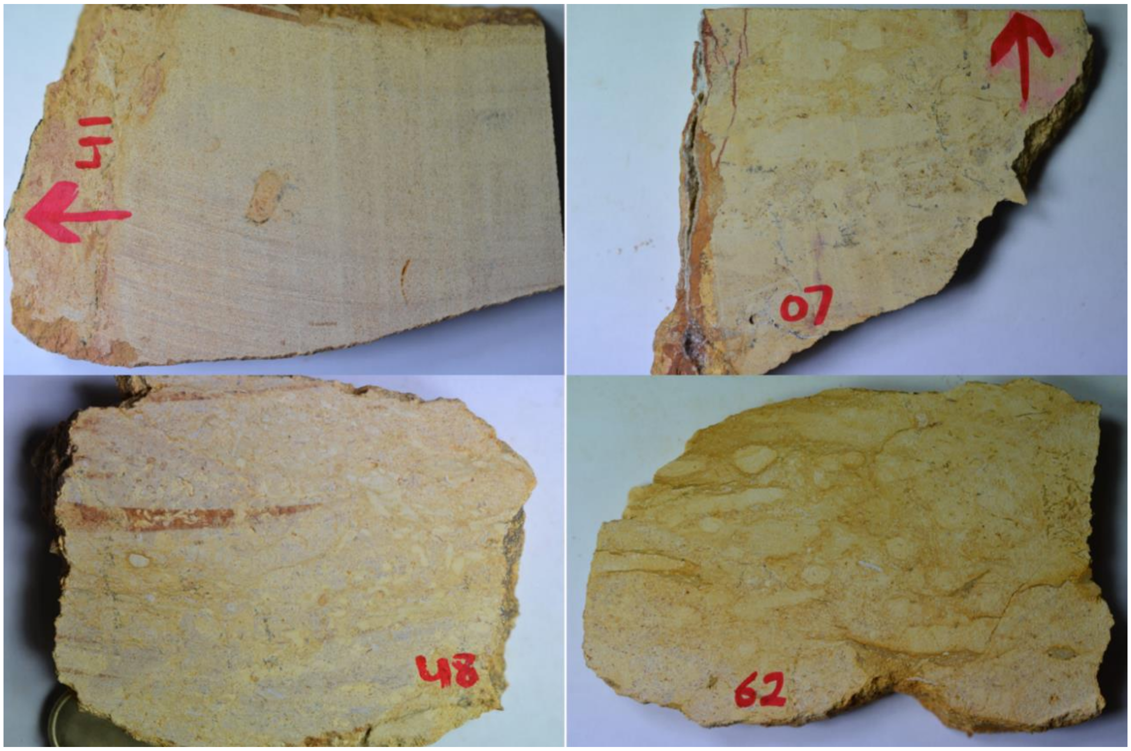


Figure 3.3: Slabs cut from the samples. These slabs are then studied in detail under optical microscope.

3.3.2 Petrographic Analysis

The slabs were further used for petrographic analysis. Thin sections were made and were studied under an optical petrographic microscope to identify rock type, the textural properties, non-skeletal and skeletal components, the cement types and visual identification and estimation of porosity types (Figure 3.4). These properties help in the determination of microfacies and biofacies of the samples.

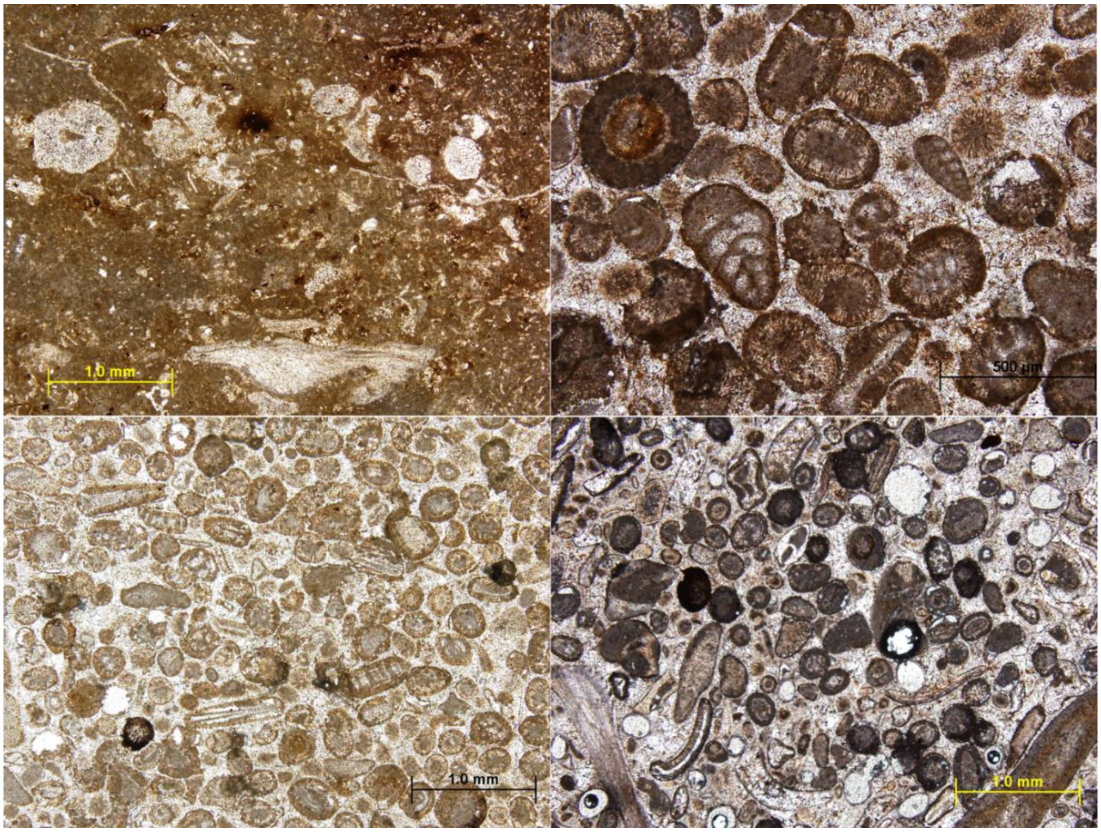


Figure 3.4: Thin sections being studied under petrographic microscope for microfacies and biofacies identification.

3.3.3 Instrumental Analysis

To aid the sedimentology data, instrumental analysis was also carried out. These include the X-Ray Florescence studies (XRF) for elemental concentrations, X-Ray Diffraction (XRD) studies for mineralogical details, and Scanning Electron Microscopy studies (SEM) for any minute details present in the samples (Figure 3.5).

Porosity measurements were not carried out due to several reasons. The visual porosity determinations were too low and also the scope of this study did not require porosity measurements to be done. In order to save time which was required for other analysis, these measurements were regarded to be beyond the scope of this project.

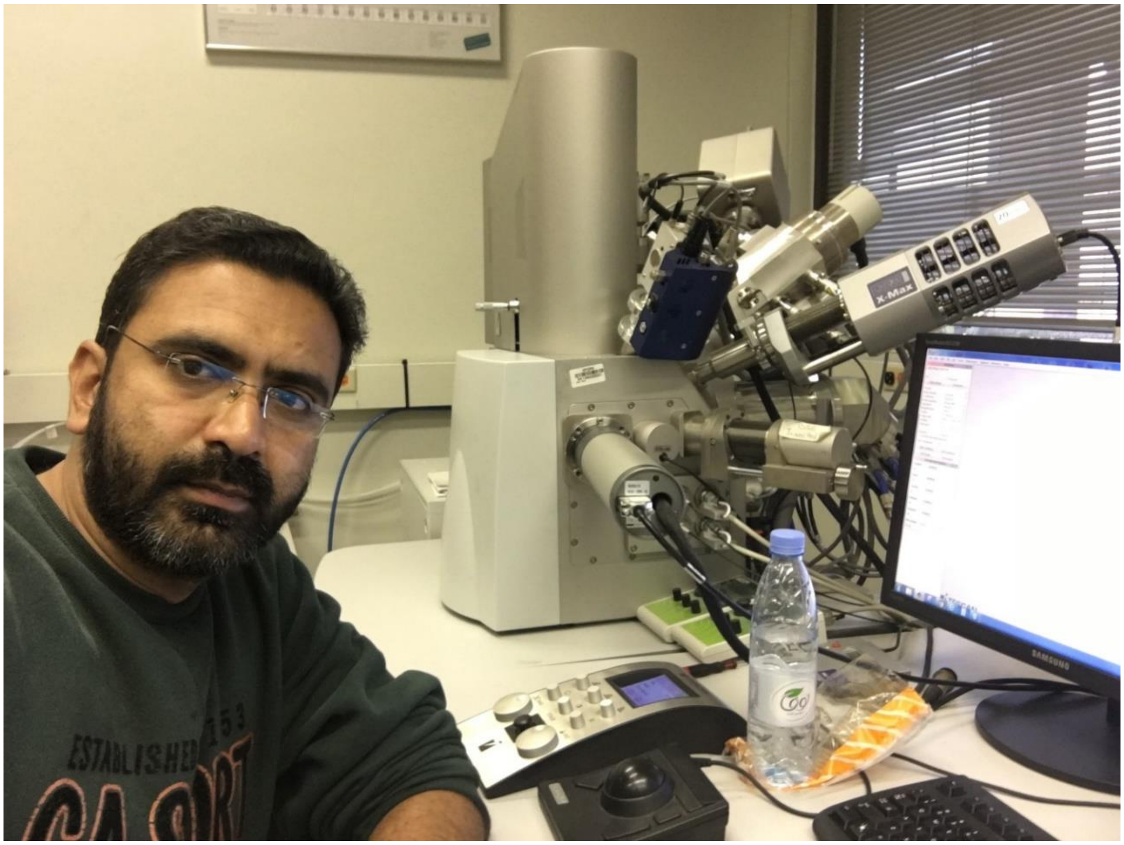


Figure 3.5: SEM analysis being carried out by the author.

3.4 Methodology applied (Micropaleontology)

3.4.1 Soap Disaggregation Method

Disaggregation of muddy samples with industrial soaps is a standard method of extracting microfossils from the light to moderately indurated muddy samples. This method requires soaking, gentle boiling and subsequent washing of sample and wet-sieving through a 63-micron sieve mesh. The process is aided by boiling the sample with industrial soap for several times. The soap acts as surfactant and disperses the clay matrix adhere to the grains and microfauna. The process is repeated until all the mud is removed. The remaining sample residue is dried, sieved and then studied under the microscope for picking of microfossils.

3.4.2 Acid Leaching Method

The acid method involves the leaching of indurated limestone samples using acetic acid. The acetic acid method was first used by Bourdon (1962), to extract ostracods from limestone samples. Several researchers (Notzold, 1965; Stouge *et al*., 1983; Thomas and Murney, 1985; Lethiers and Crasquin-Soleau, 1988; Wernli and Görög, 1999; Lirer, 2000; Holcová, 2002; Reolid 2004; Patruno et al. 2011; Hjálmarsdóttir et al. 2011; Coccioni and Premoli-Silva, 2015) have successfully used the method and modified it by using different acid concentrations and reaction times (6 hours to 40 days), and different sample sizes to extract foraminifera from hard, lithified argillaceous limestones. In this study, this method to extract microfossils from hard limestones samples. This is the first time the Acetic acid leaching method is used in Saudi Arabia for any Jurassic samples.

The samples were treated with acetic acid using the following steps given below (Figure 3.6):

1) 100 g of carbonate sample was broken down into small fragments of about 2 to 5 mm. The small size of fragments is recommended as acid reacts readily with them, and will give better results. However, during crushing of the samples, care is required to make sure that the microfossils are not destroyed.
2) Crushed samples are then placed in glass beakers and are properly labeled.

3) Solutions of 80% of acetic acid (CH_3COOH) mixed with 20% distilled water were used to disaggregate the samples (the level of the acetic acid / water mixture should be at least 2 cm above the sample level).
4) The submersed samples are left in the solution overnight, for at least 10 to 15 hours, to help the disaggregation process.
5) The residue was washed and dried at low temperature (40-50°C) above a hot plate.
6) The disaggregated samples were then sieved through stainless steel standard sieves with mesh openings of 1.00 mm, 0.50 mm, and 0.063 mm.
7) The sample residues were transferred to labeled small sample vials. The foraminiferal specimens contained in the residues were sorted using a binocular stereo microscope.

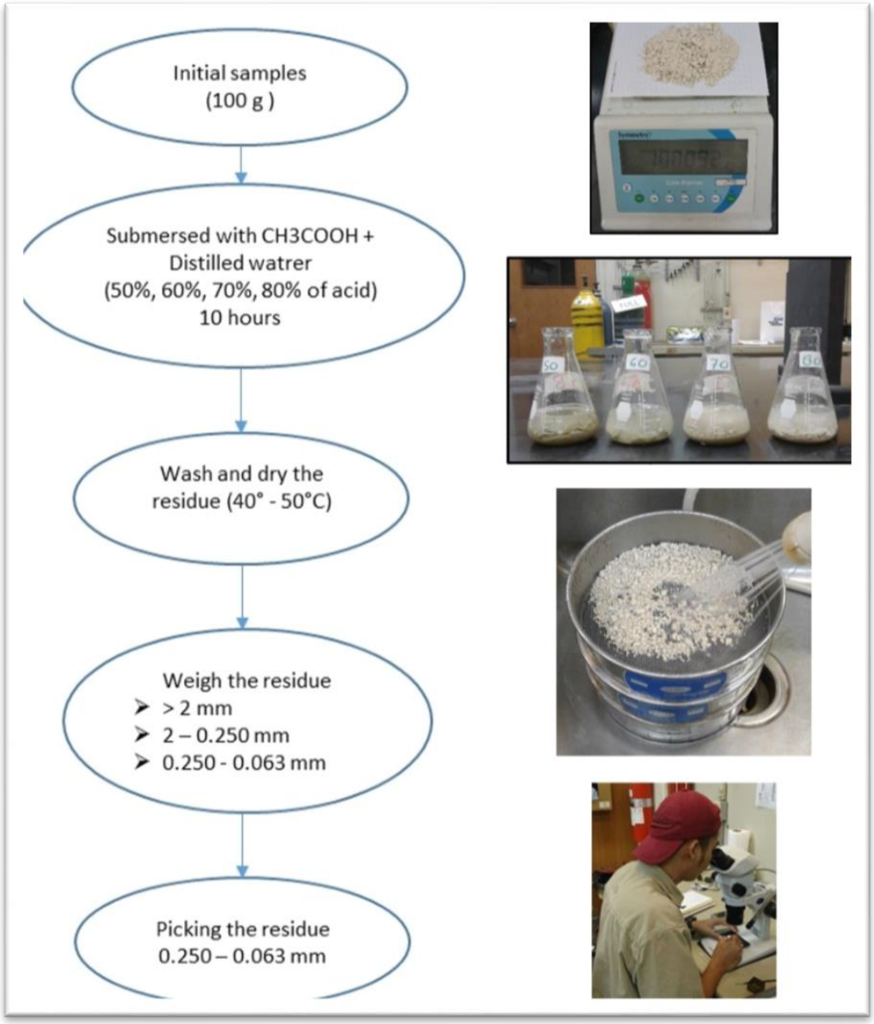


Figure 3.6: Generalized flow chart of acid leaching method carried out for fossil extraction form hard limestone samples.

The recovery of microfossils was assessed by weighing the residue, and 300 specimens were picked from each sample. The quality of the sample residue was then visually assessed to determine the preservation state of the recovered specimens. Both dissolved and partially- or undissolved specimens (specimens that still have matrix attached) were picked and counted. Representative specimens were photographed using a Nikkon-1500 microscope (Figure 3.7).

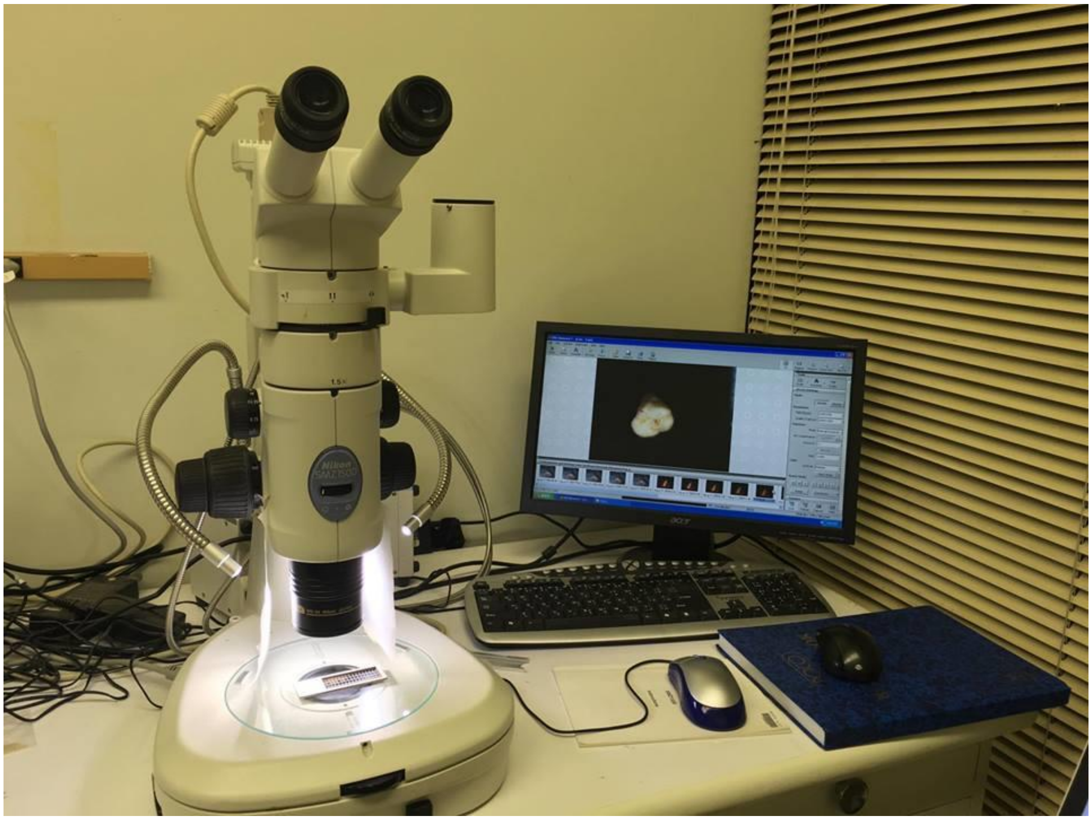


Figure 3.7: Samples picked from the residue being photographed by Nikon 1500 microscope

CHAPTER 4

RESULTS

SEDIMENTOLOGY

4.1 Introduction

To understand the depositional environment of D4 and D5 members of Middle Jurassic Dhruma Formation, lithofacies analysis was done with the help of thin section studies. Thin sections made from the representative samples were studied under the petrographic microscope. Facies were decided based on the sedimentary structures, Dunham texture, grain size, dominant non-skeletal grains and bio-components. Field descriptions were also kept in mind while naming the facies. A lithological log was prepared with the help of all available data showing the field description in details along with the detailed study been done in the laboratory. The samples identified with different lithofacies have also been indicated (Figure 4.1). These results were further aided with geochemical studies of the samples. X-Ray fluorescence and X-Ray diffraction techniques were used on the same samples to know their elemental and mineralogical composition respectively. The results were further strengthened by the scanning electron microscope images to see the texture of the rocks under high magnifications.

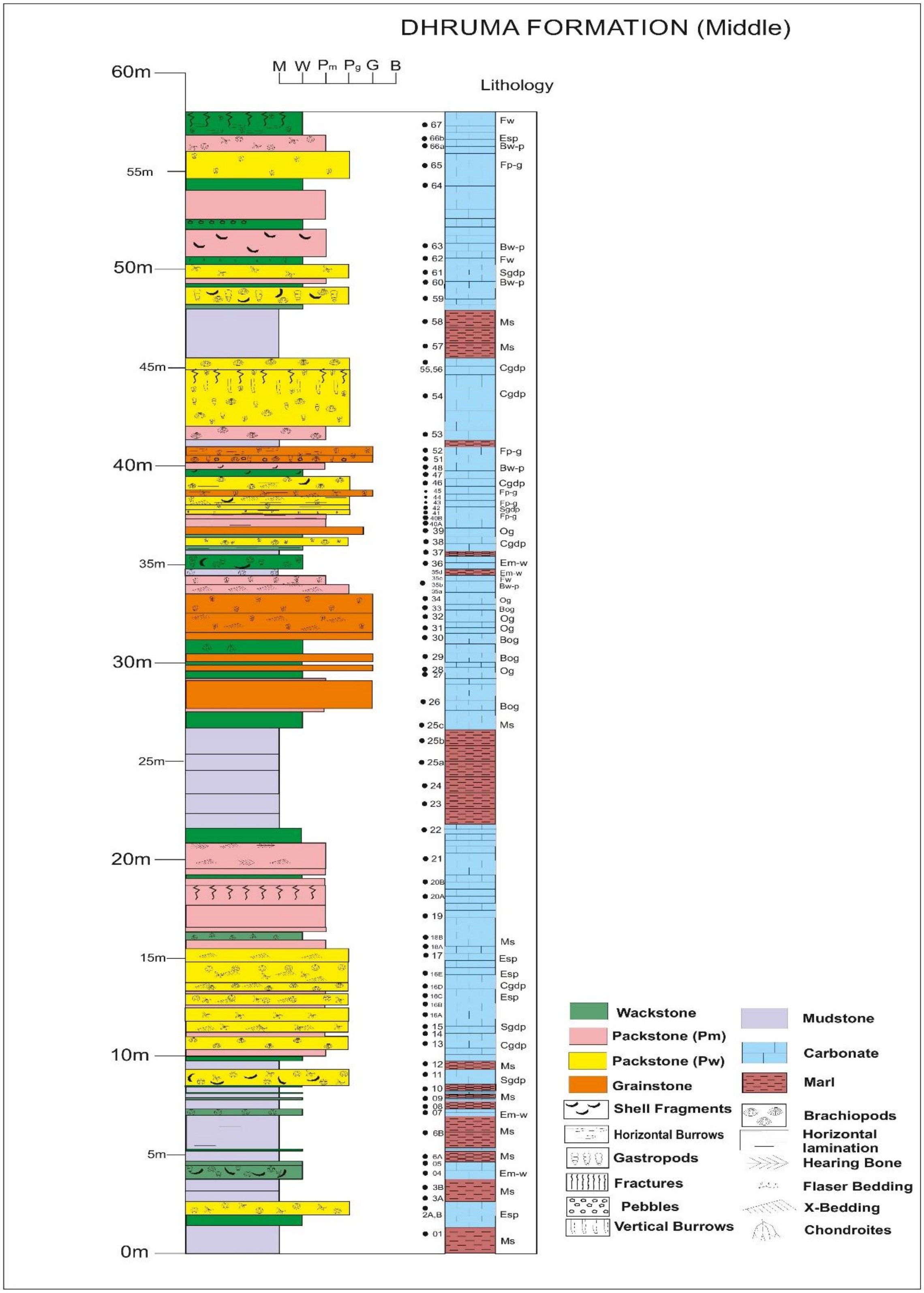


Figure 4.1: The lithologic log reflecting the outcrop of Middle Jurassic D4 & D5 members of Dhruma Formation.

4.2 Lithofacies Identified

The thin section results show the presence of about 10 different lithofacies in the study area based on Dunham's classification scheme. The lithofacies range from mudstones, mudstones to wackestone, wackestone to packstone and to oolitic grainstones. The facies were named on the presence of dominating texture or biofacies. Identified facies show a wide distribution of texture and grain-type and hence the changes in the sea-level and depositional environment. The facies are repeated at different intervals which help us in describing the different sequences as the sea-level fluctuates. Different lithofacies identified are given below in details as per their abundance in the study area. The most dominant is described first and the least one last. Mudstones although being the most common are described in the last due to lack of thin-section data. The identified lithofacies are given below and their distribution in the outcrop is shown in Figure 4.2:

1. Coral bearing grain dominated packstone facies (Cgdp)
2. Echinoderm bearing spicule rich packstone facies (Esp)
3. Oolitic grainstone facies (Og)
4. Bioclastic wackestone/packstone facies (Bw-p)
5. Foraminiferal packstone/grainstone facies (Fp-g)
6. Echinoderm rich mudstone/ wackstone facies (Em-w)
7. Bioclastic oolitic grainstone facies (Bog)
8. Foraminiferal wackestone facies (Fw)
9. Spicule rich pelloidal grain dominated packstone facies (Spgdp)
10. Mudstone facies (Ms)

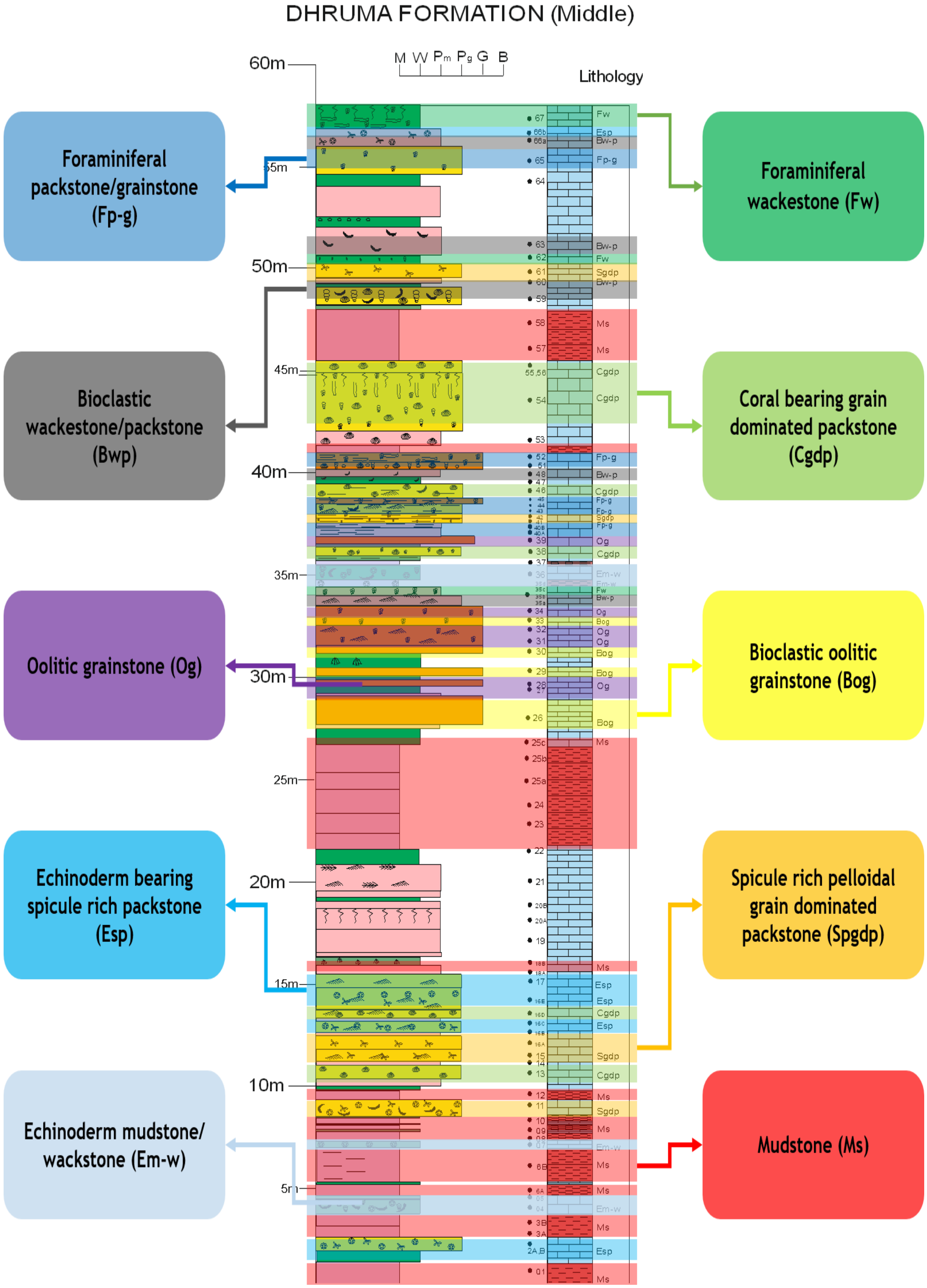


Figure 4.2: Identified lithofacies distribution in the outcrop. Representative colors are given to each lithofacies.

4.2.1 Coral bearing grain dominated packstone facies (Cgdp)

Coral bearing grain dominated packstone facies is the most abundant facies in the study area after the mudstones. In the outcrop, Cgdp facies are characterized by thick bedded light colored limestones with cross bedding (Figure 4.3 a, b). Some of the beds start with the hard grounds at the base. When studied under thin sections, this facies is composed of grain rich packstones which are dominated by corals of large size. Other skeletal grains include brachiopods, echinoderm fragments, bivalves, sponge spicules and rich foraminifera. The non-skeletal grains include mostly pelloids, some ooids and pellets. Corals overgrowth on brachiopods is also observed in few specimens (Figure 4.3 c, d).

High intensity of diagenesis is observed with corals showing dissolved boundaries filled with secondary materials, replaced pelloids, some partially and some fully replaced echinoderms by pelloid grains. Geopetal structures are also seen arching the echinoderm fragments. Iron rich cement is present in most of the observed samples. The facies show porosity of 5-10% of different types including moldic, vuggy and intragranular porosity as seen in large coral fragments. Organic matter is also observed in few samples.

SEM photographs of the facies show fine micrite cement with some well-developed calcite crystals (Figure 4.3 e, f). The facies is mostly calcite rich with as seen in XRD analysis. Iron is also present in small quantities along with Mn, Al, Si and Cr while Ca is the major element found in XRF analysis (Figure 4.4 a, b).

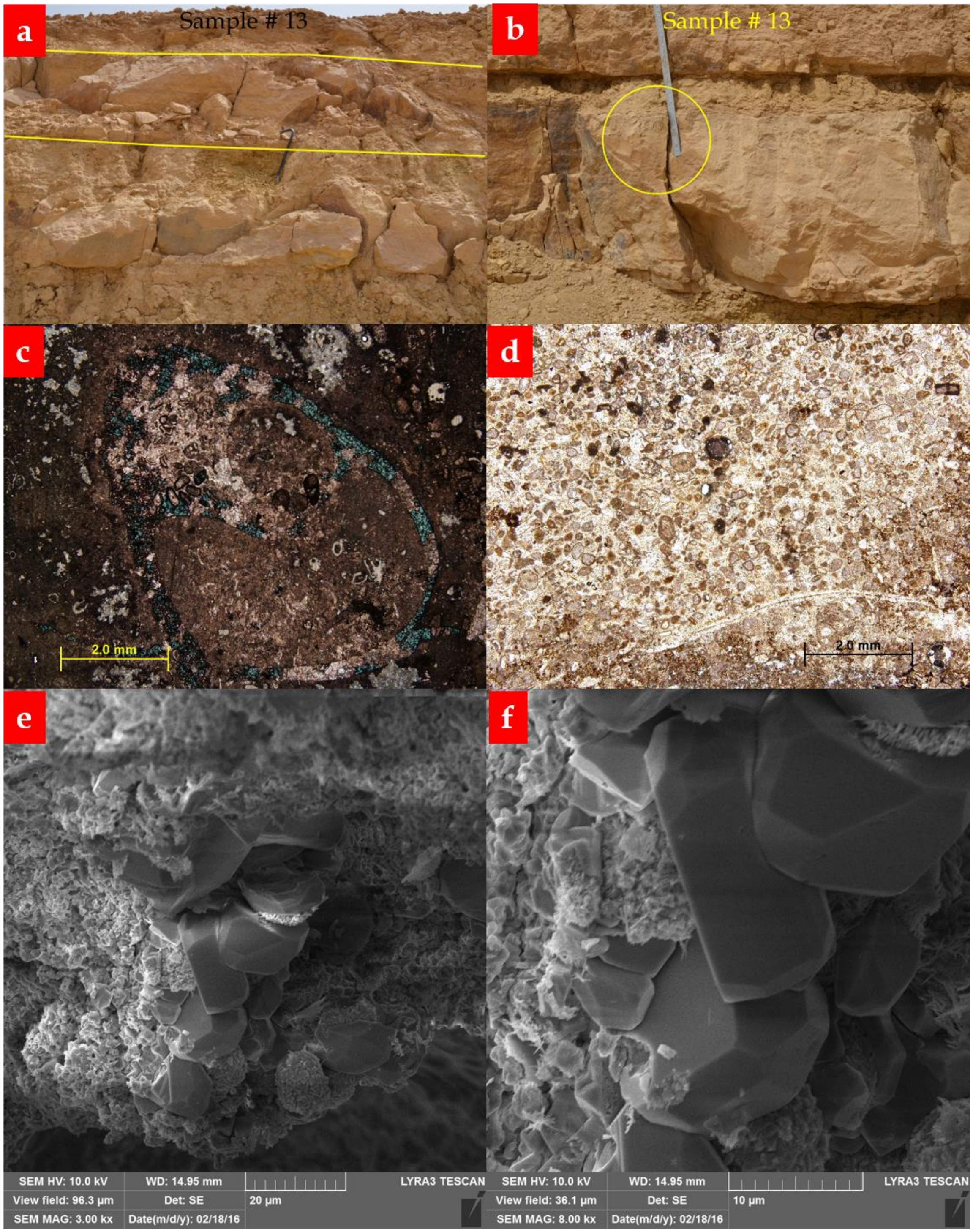


Figure 4.3: (a) Outcrop image of the sample location-broad view showing hard limestone beds interbedded in marly layers. (b) zoomed view of the sample showing thick bedded limestone layers with sedimentary structures. (c)Thin section showing a coral with dissolved boundaries. (d) Thin sections made from the sample showing the dominance of grains in the facies. (e) (f) SEM Images showing calcite crystals in fine matrix.

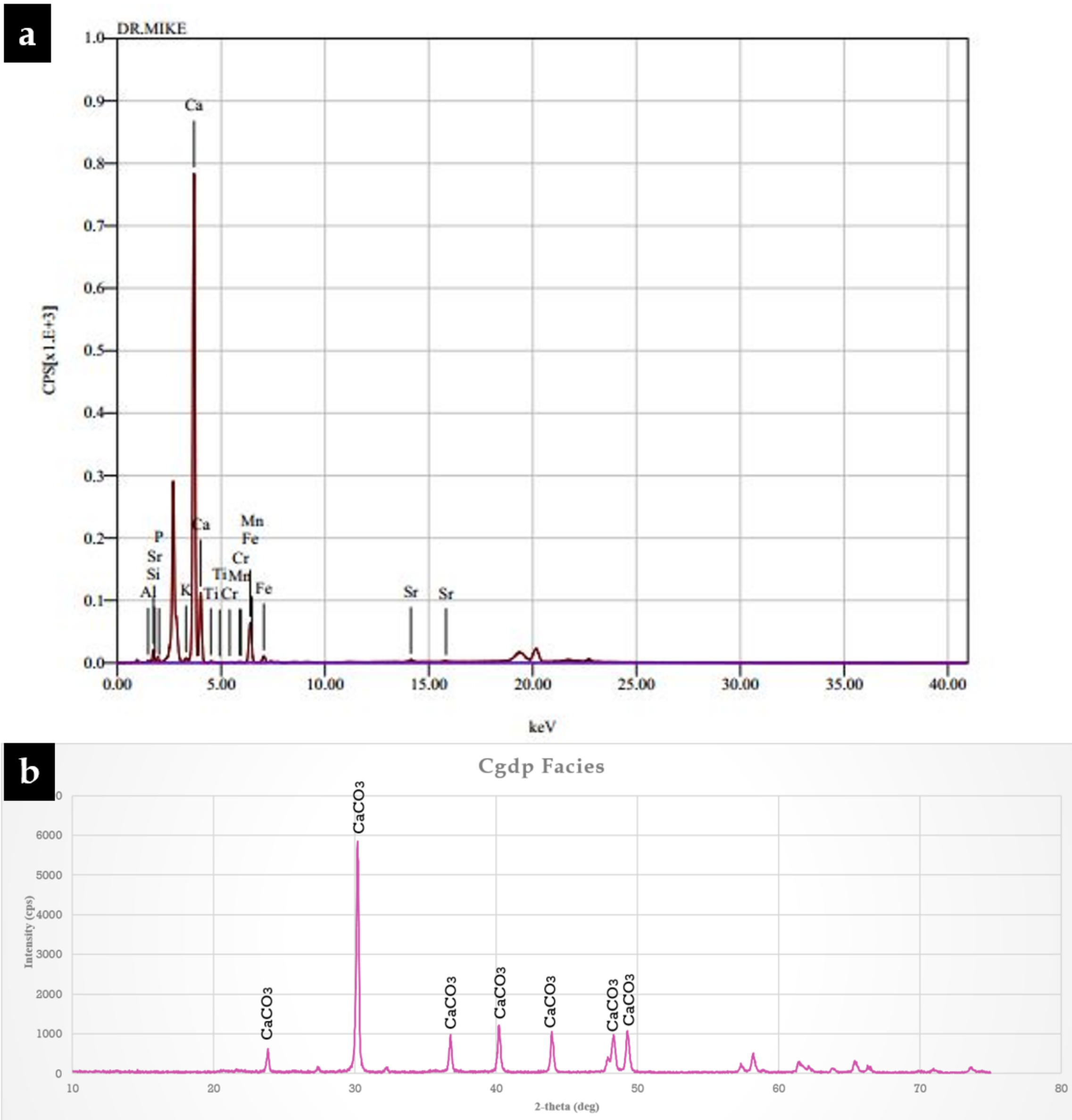


Figure 4.4: (a) XRF data showing the distribution of elements with no traces of Magnesium. (b) XRD results showing calcite as the major element with no traces of dolomite.

4.2.2 Echinoderm bearing spicule rich packstone facies (Esp)

Among all the facies encountered in the study area, echinoderm spicule rich packstone facies is the second most abundant facies. The facies is mostly encountered in the basal portion of the outcrop with some presence near the top of the outcrop. In the outcrops, facies are represented by thick bedded hard limestone beds of light creamy to yellow color mainly. The beds are rich in burrows which are filled by secondary materials. Some bivalves, trigonia and broken fragments of shells are also seen on the bedding surfaces (Figure 4.5 a, b). In thin sections, the facies is mostly consistent of mud supported packstone with mud content of 55 to 60%. Some samples with less mud content are also encountered but overall no big difference in texture is observed. The facies is rich in skeletal grains specially echinoderm fragments, sponge spicules, bivalves, brachiopods, algae, foraminifera and some broken shell fragments. Non skeletal grains are rare and only some pelloids are observed (Figure 4.5 c, d).

Effects of diagenesis are also visible in some sections with dissolved corals and grains with no internal structure. The echinoids also show some Syntaxial overgrowths to replace brachiopod fragments in some samples. Porosity is not evident from the thin sections and only some samples show only 5% porosity of intergranular to buggy types. Some organic matter is also seen in samples.

Scanning electron microscope result of the facies shows fine-grained matrix with few calcite crystals (Figure 4.5 e, f). The XRD results show the presence of calcite mostly and nearly all the evident peaks belong to CaCO3. There is not much evidence of dolomitization in the samples except one and no Mg is observed in the XRF analysis also (Figure 4.6 a, b).

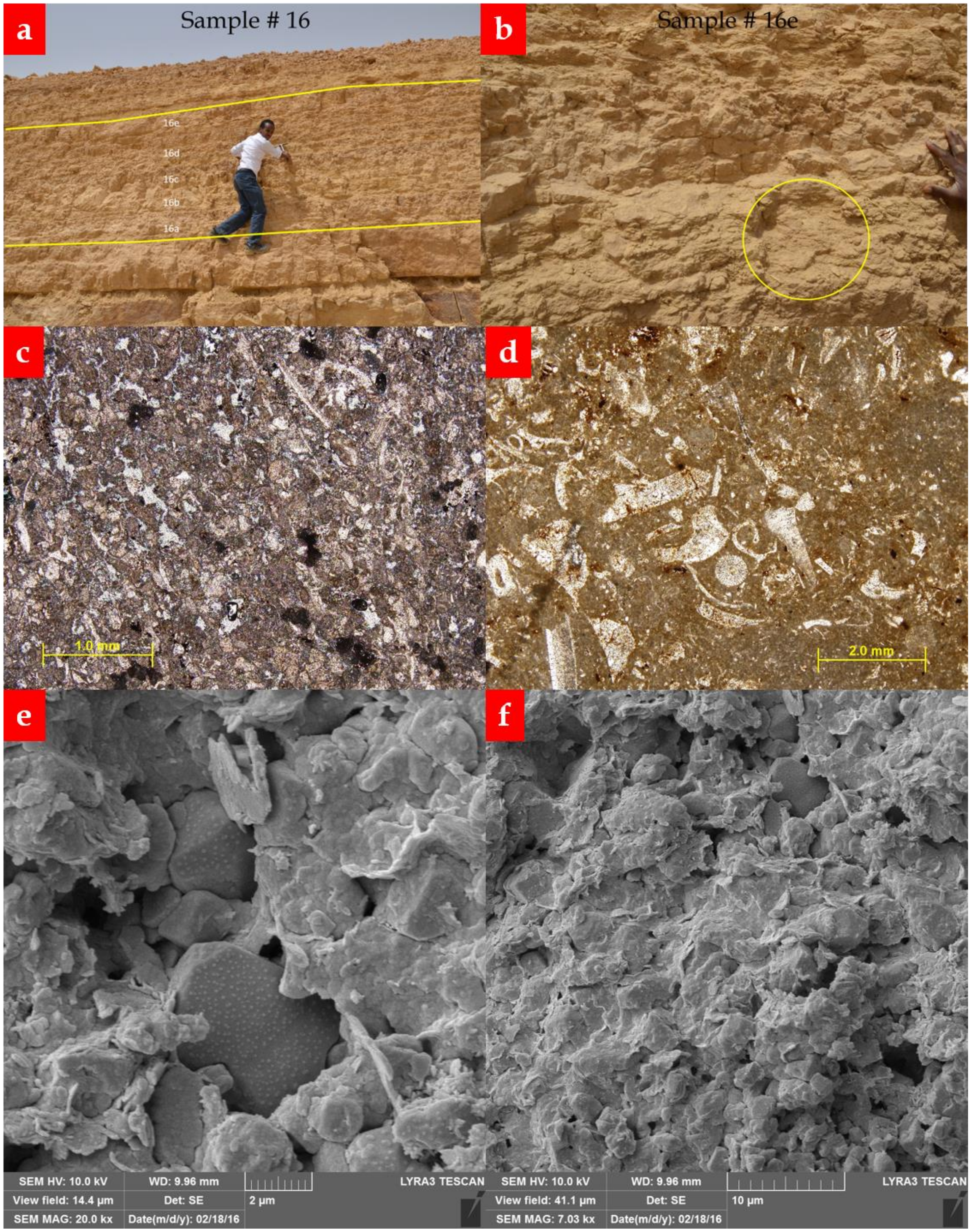


Figure4.5: (a) Outcrop images showing the sample location with thick limestone beds stacked and amalgamated. (b) Zoomed in image showing some sedimentary features at the bed of sample. Most of features are not evident due to weathering. (c)(d) Thin section images of the samples showing richness of echinoderms and spicules in Esp facies embedded in fine mud. (e) (f) SEM images showing calcite crystals in fine grained matrix.

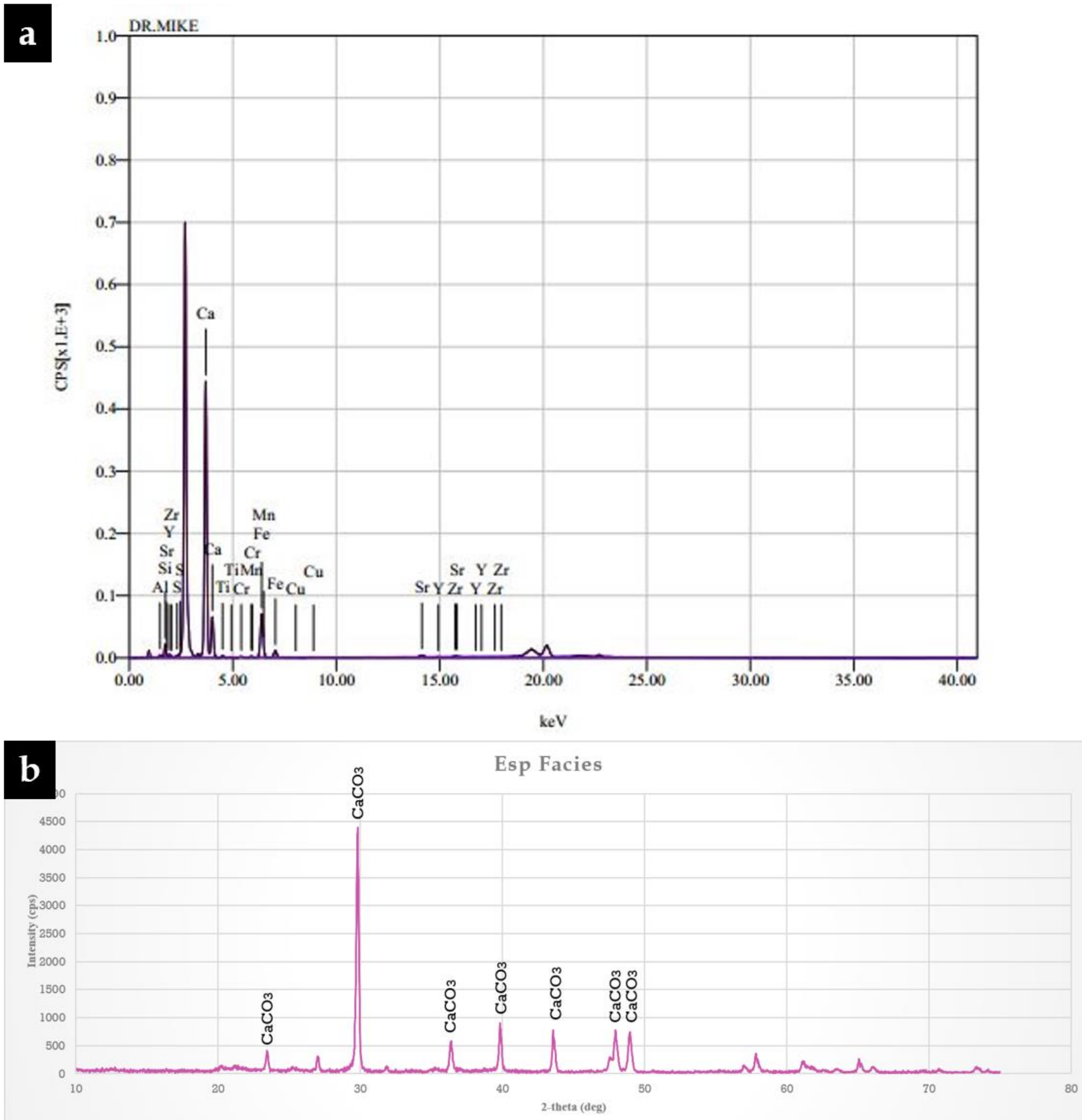


Figure 4.6: (a) XRF data showing the distribution of elements. (b) XRD results showing calcite as the major element with no traces of dolomite.

4.2.3 Oolitic grainstone facies (Og)

Oolitic grainstone is also one of the major facies encountered and is mostly found in the central portion of the outcrop. In the outcrop, Og facies is characterized by light colored, large to medium scale stacked amalgamated beds of coarse to medium grained grainstone limestone beds with evident herringbone crossbedding showing decrease in water energy. The limestone rusts to greenish color on weathered surface (Figure 4.7 a, b). When studied under thin sections, the facies consist of both skeletal and non-skeletal grains. Skeletal grains include echinoderms, bivalves, corals, brachiopods and foraminifera. Non skeletal grains mostly consist of ooids which are present more than 50% in some samples and sometimes more than 80% in others. Along with ooids some pelloids and structure less pellets are also observed.

High cementation is seen within the samples with some samples showing alteration of grains with the cement. Rimmed cement is observed around some ooids. Some echinoderms coated with cement are also seen (Figure 4.7 c, d). Evidence of diagenesis are evident from altered and dissolved grains of echinoderms, dissolved molluscs and some elliptical and fused ooids. The facies is rich in benthic foraminifera which are picked and studied.

Scanning electron microscope studies of the facies show fine-grained cement and no other evident features are observed. The XRD analysis of the facies show rich calcite content with CaCO3 as the major mineral. Again no Mg is seen in XRF analysis while other elements like Fe, Mn, Si, Ti and K are present in smaller quantities (Figure 4.8 a, b).

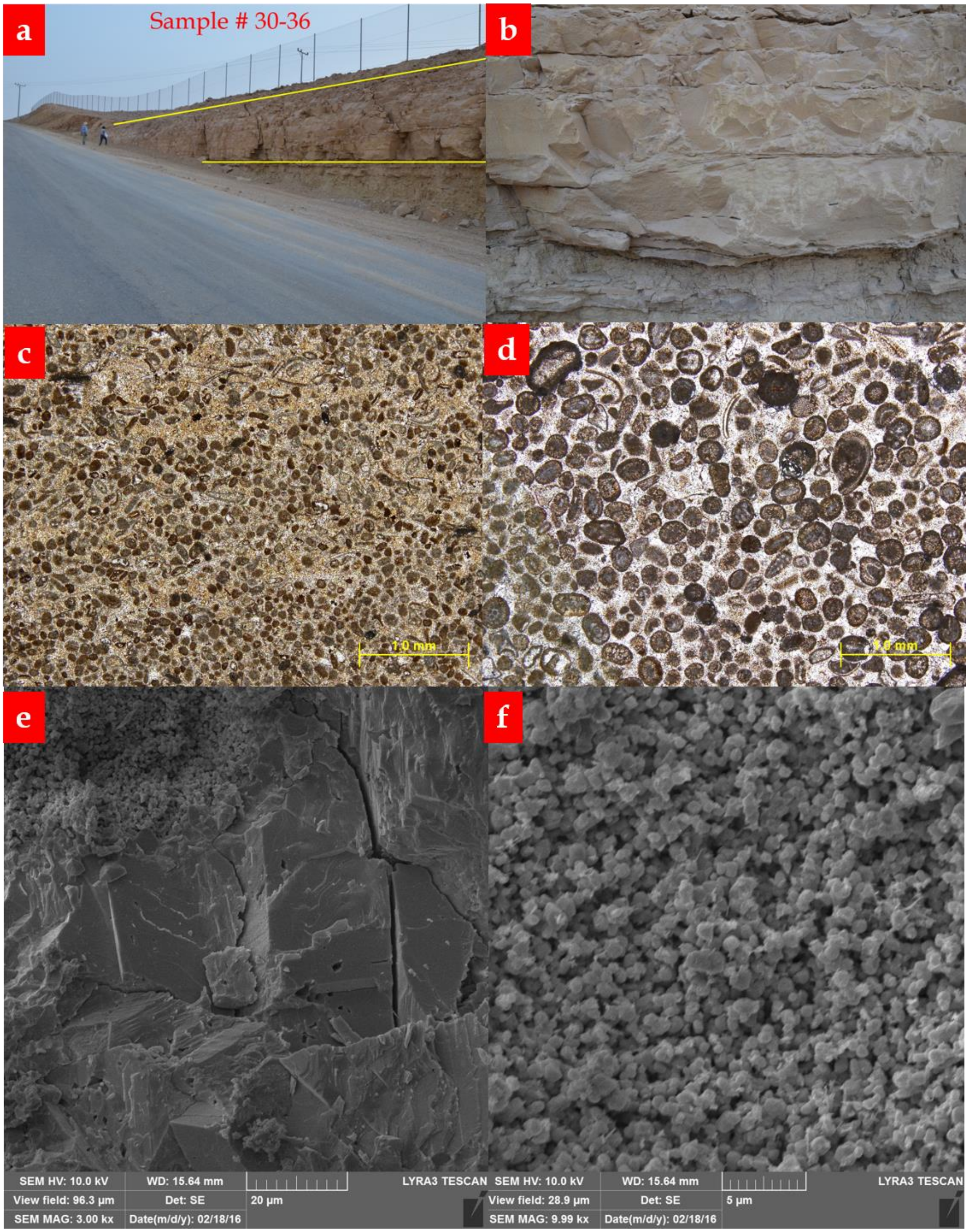


Figure 4.7: (a) Outcrop images showing the thick oolitic beds stacked and amalgamated. (b) Zoomed in image showing some sedimentary features at the bed of sample including small scale cross bedding and horizontal lamination. (c) (d) Thin section images of the samples showing rich oolites along with other skeletal and non-skeletal grains of Og facies. (e) (f) SEM images showing the fine grained texture of facies.

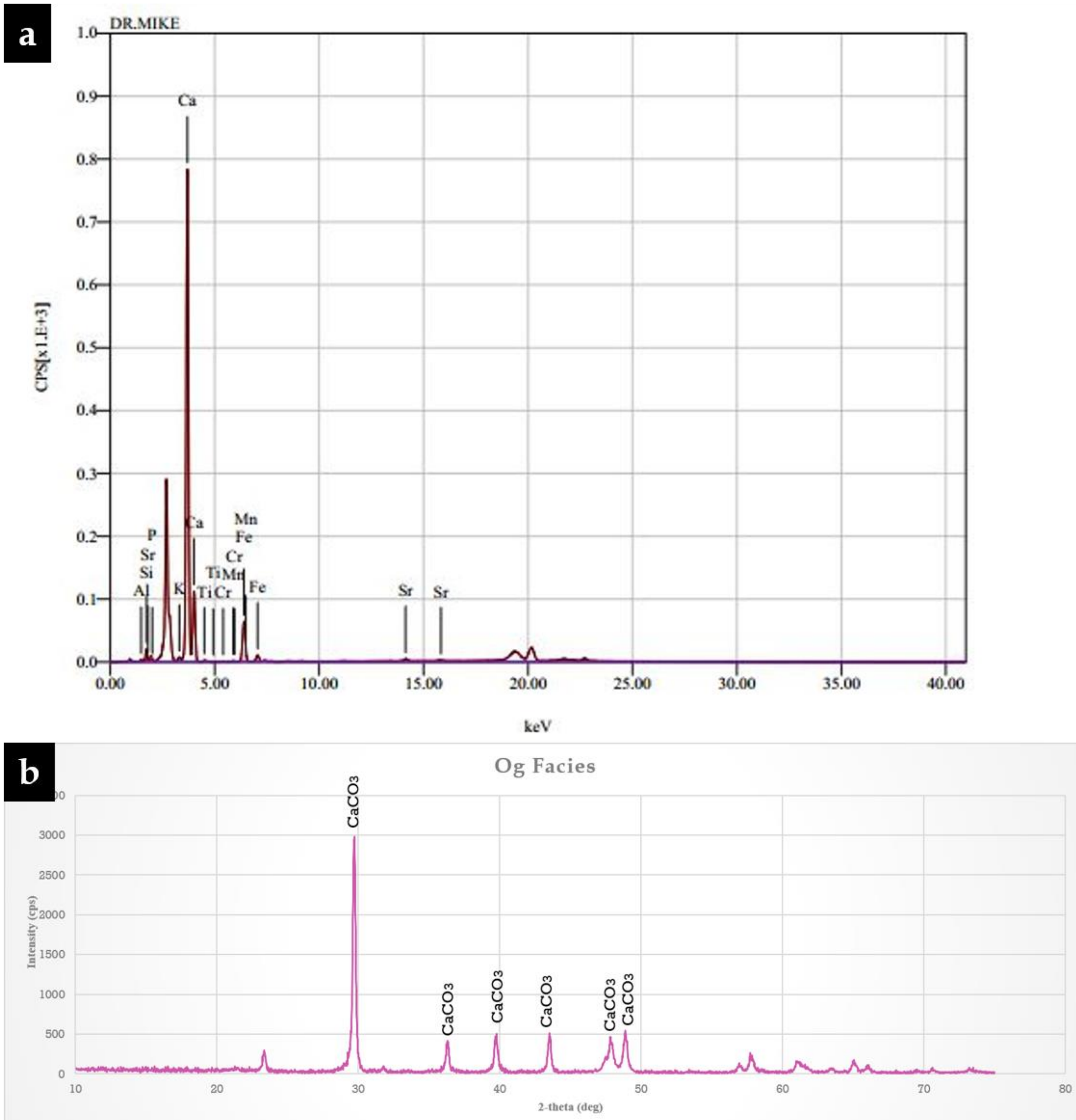


Figure 4.8: (a) XRF data showing the distribution of elements. (b) XRD results showing calcite as the major element with no traces of dolomite.

4.2.4 Bioclastic wackestone / packstone facies (Bw-p)

The Bioclastic wackestone to packstone facies is mostly observed in the middle and upper portion of the outcrop. In the outcrop the facies is represented by light colored reddish yellow marly limestone beds with burrows. The beds also contain smaller shell fragments and some bivalves embedded in them. The limestones are mostly friable with a few exceptions (Figure 4.9 a, b). When studied under thin sections, the facies consists of bioclastic mud rich wackstone to packstones texture. Bioclastic skeletal grains include brachiopods, echinoderms, corals, bivalves, spicules and foraminifera. Non skeletal grains include mostly pelloids.

Some of the specimens show well preserved internal structure of grains while others show some evidences of diagenesis where corals have been replaced by other skeletal grains (Figure 4.9 c, d). Sometimes organic matter is also found associated with the corals. Mud is the major constituent of most of the samples while its percentage decreases in some leading it more towards the grainy packstone facies. Porosity is sparse in the facies with only few samples showing 5 – 10% porosity.

The XRD analysis of the samples indicate mostly calcite as major mineral. Other than Calcium which is the most abundant element, Iron, Zinc and Manganese are also seen in XRF analysis (Figure 4.10 a, b). Scanning electron microscope data shows fine grained muds with few calcite crystals (Figure 4.9 e, f).

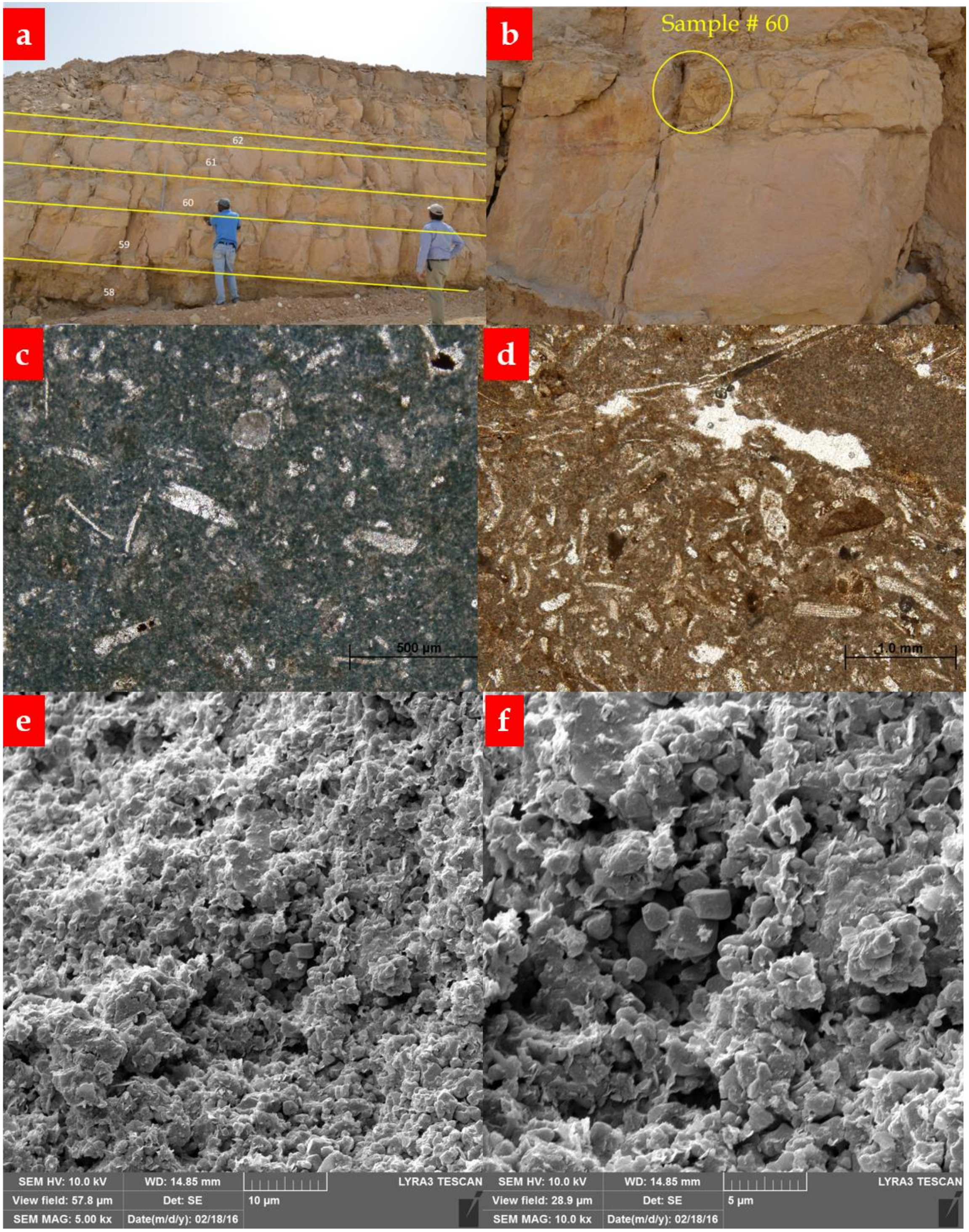


Figure 4.9: (a) Outcrop images showing the sample location in-between thick bedded limestone layers. (b) Zoomed in image showing some sedimentary features at the friable bed of sample. Small scale fractures are also seen. (c) (d) Thin section images of the samples showing bioclastic fragments present in muddy fabric of Bw-p facies. Some foraminifera can also be seen. (e) (f) SEM images showing the very fine grained texture of facies.

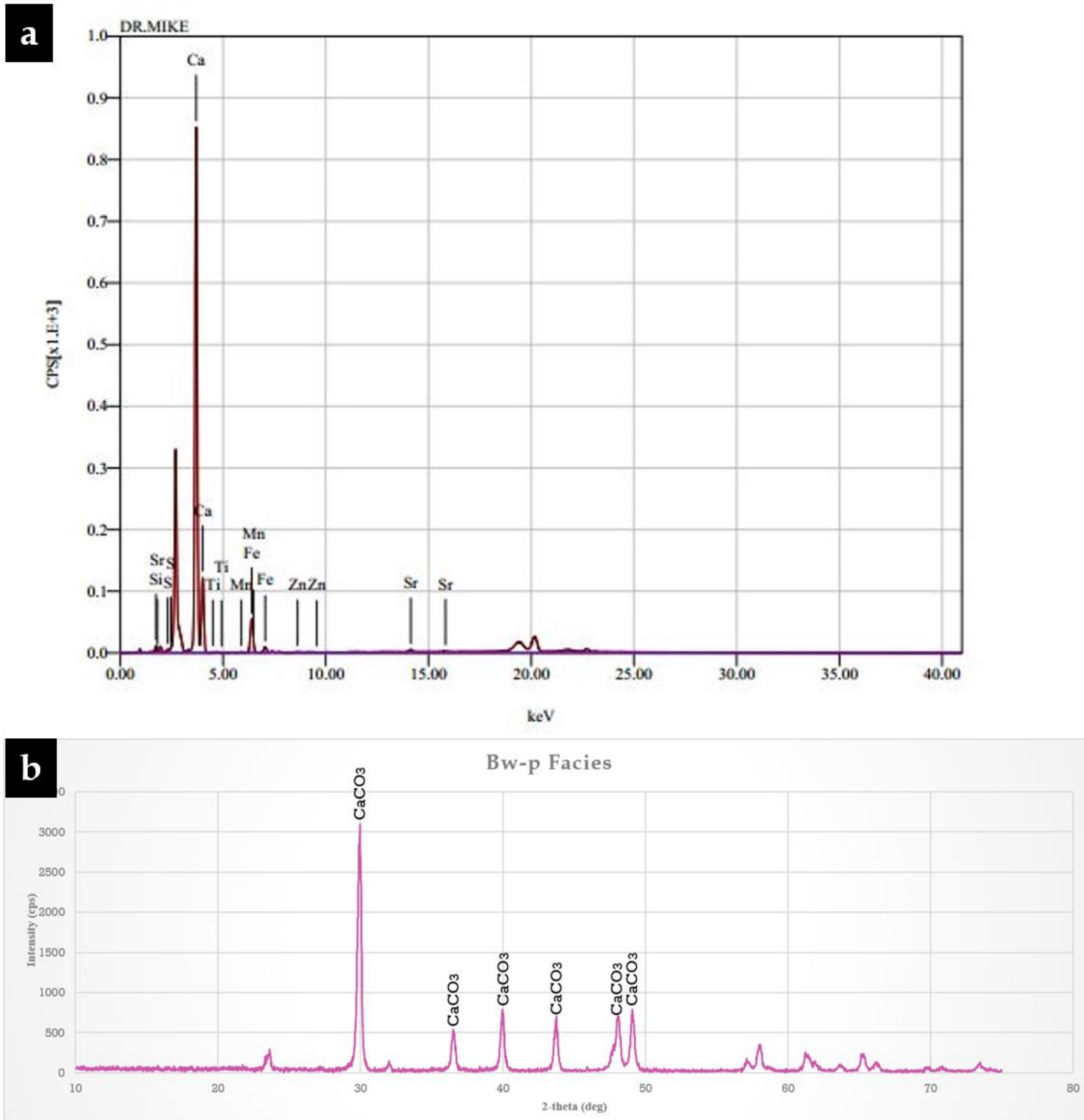


Figure 4.10: (a) XRF data showing the distribution of elements. (b) XRD results showing calcite as the major element with no traces of dolomite.

4.2.5 Foraminiferal packstone / grainstone facies (Fp-g)

Foraminiferal packstone to grainstone facies is mostly encountered in the upper portion of the location which mostly consists of upper D5 member of the Dhruma Formation. In the outcrop, the facies is represented by thin (10-15cm) beds of limestone which is hard in the lower part but becomes friable as we move to the upper part of the outcrop (Figure 4.11 a, b). Small scale cross bedding and horizontal lamination is also present along with burrows. When studied under thin sections, the facies is mostly composed of foraminifera along with some other skeletal grains like echinoderms, sponge spicules and bivalves. Corals are also present in few samples while in others corals are either totally replaced by other bioclastic material or are micritized. The facies is highly cemented, micritized and compacted. Foraminifera are abundant in the samples and some forams can be seen penetrating other grains (Figure 4.11 c, d). Small percentage of vuggy porosity (3-5%) is seen in some samples. Organic matter is also present in most of the samples of this facies.

Scanning electron microscope images show fine grained micrite (Figure 4.11 e, f). The samples are mostly mineralogically composed of calcite. There was not any evidence of dolomitization observed in XRD results. XRF results show the presence of small quantities of Mn, Fe, Zn and Copper along with Calcium which is the major element (Figure 4.12 a, b).

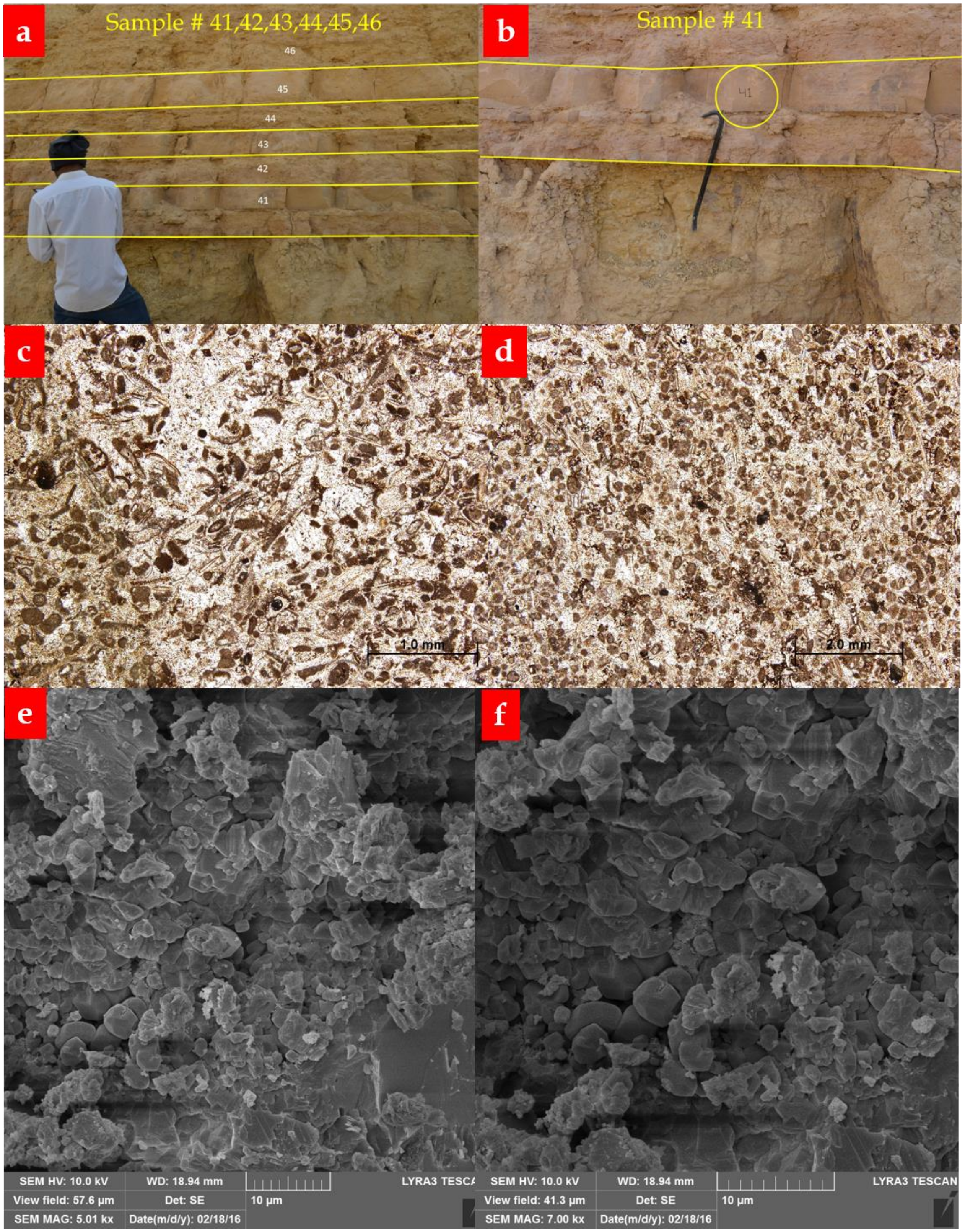


Figure 4.11: (a) Outcrop images showing the sample located in thick layers of limestone interbedded with marls. (b) Zoomed in image showing some sedimentary features at the bed of sample. (c) (d) Thin section images of the samples showing foraminifera rich texture along with other skeletal and non-skeletal grains in Fp-g facies. (e) (f) SEM images showing the micritization.

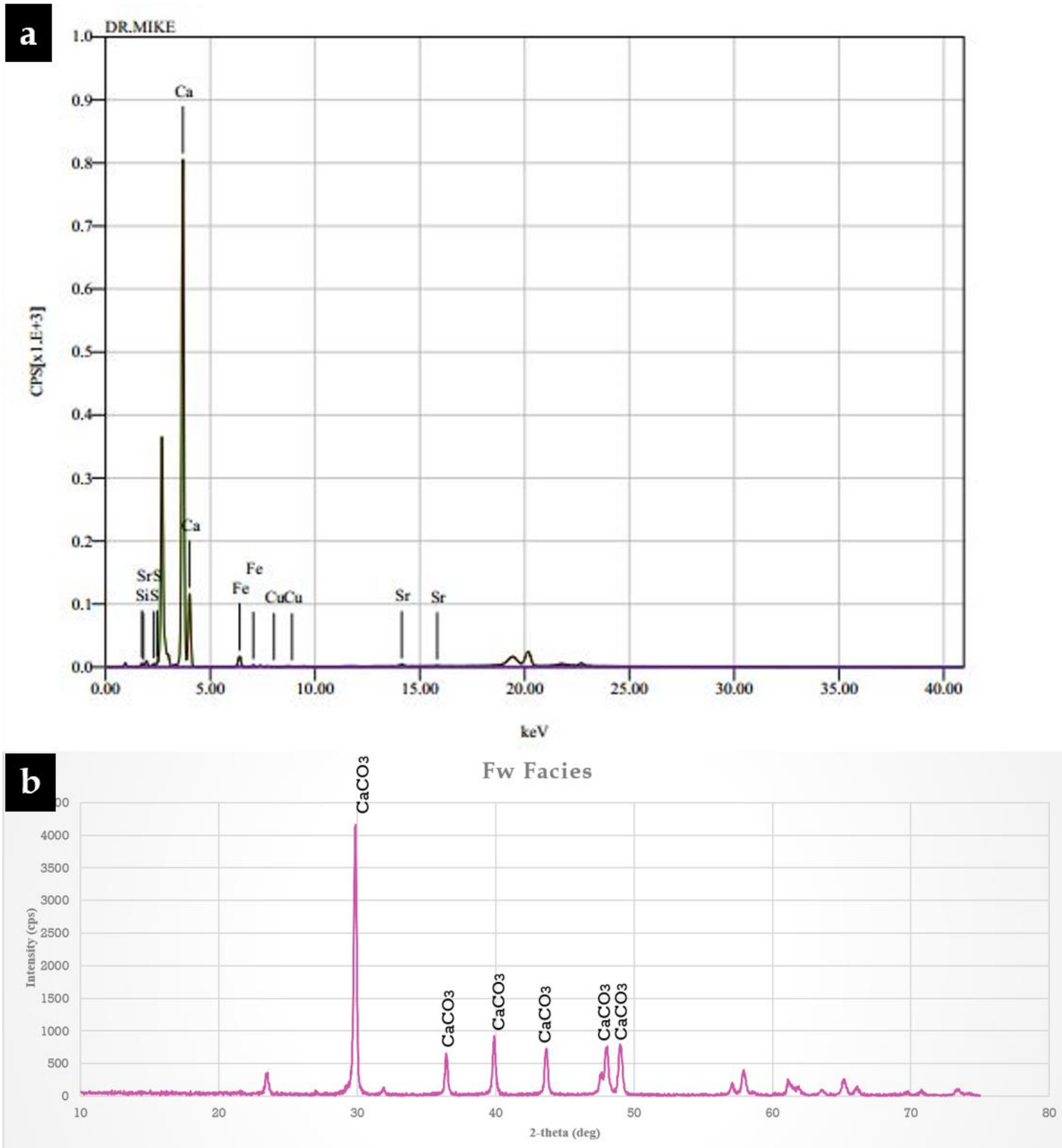


Figure 4.12: (a) XRF data showing the distribution of elements. (b) XRD results showing calcite as the major element with no traces of dolomite.

4.2.6 Echinoderm rich mudstone / wackstone Facies (Em-w)

This facies is found in mostly lower and middle portion of the outcrop mostly corresponding to the lower D5 member of Middle Dhruma Formation. In the outcrop, Em-w facies is represented by hard structure less limestone beds. The beds contain bivalve shells along with other smaller shell fragments (Figure 4.13 a, b). When studied under thin sections, the facies consists of mostly mud with skeletal grains including echinoderms, bivalves, sponge spicules, brachiopods and foraminifera. The non-skeletal grains include pelloids, pellets, ooids and some bituminous dendritic material. Syntaxial overgrowth of cement can be seen around the echinoderms (Figure 4.13 c, d). Evidences of diagenesis are also observed as internal structure of some echinoderms and corals is lost with some secondary infillings of bioclastic matter and sometimes pelloids. Organic matter is also present in the samples. The Em-w facies show up to 5% porosity which is mostly fracture porosity.

The facies shows no evidence of dolomitization which is confirmed by XRF analysis where no Mg is found in the samples (Figure 4.14 a, b). XRD analysis of the samples show abundance of calcite which can also be seen in the SEM images (Figure 4.13 e, f).

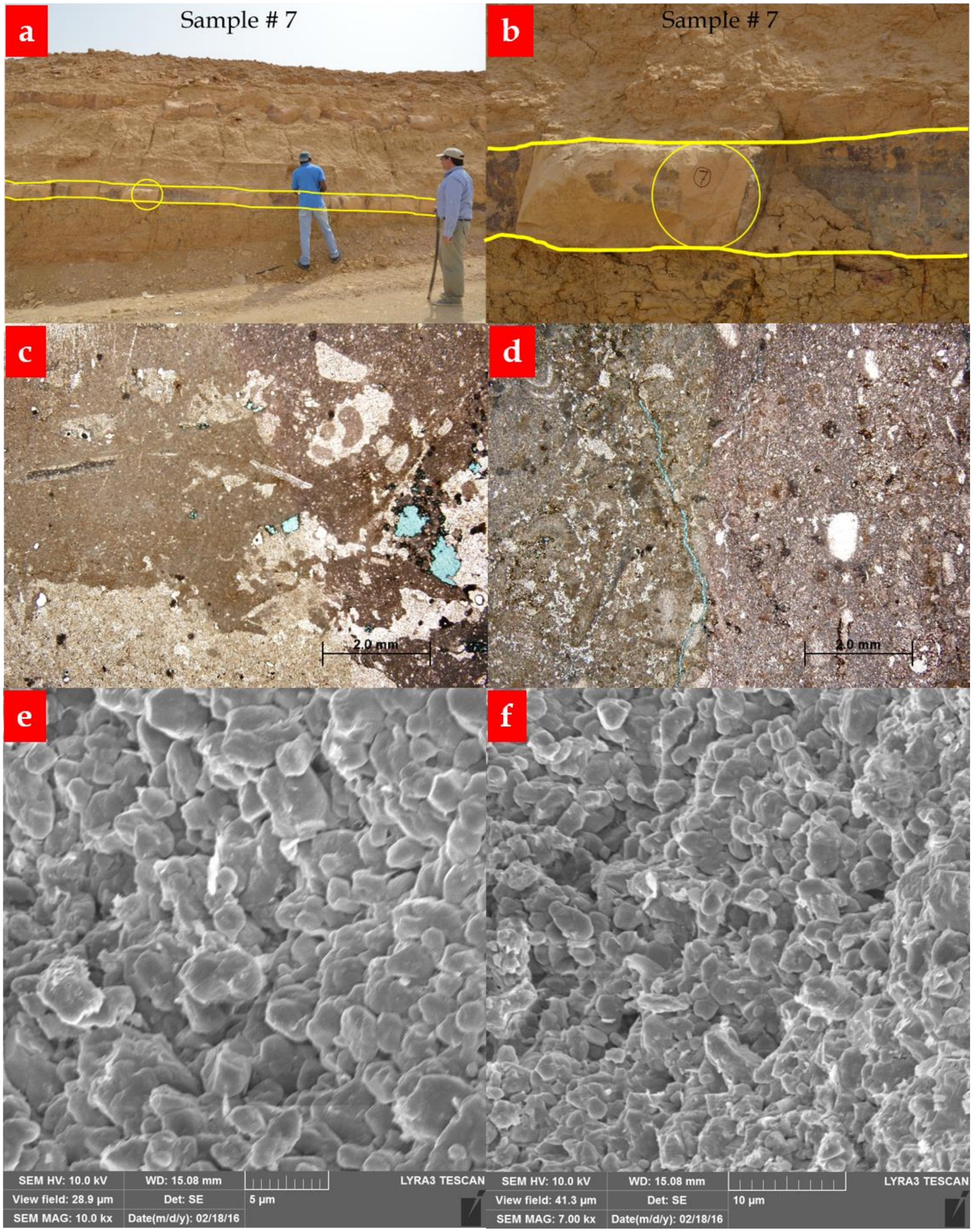
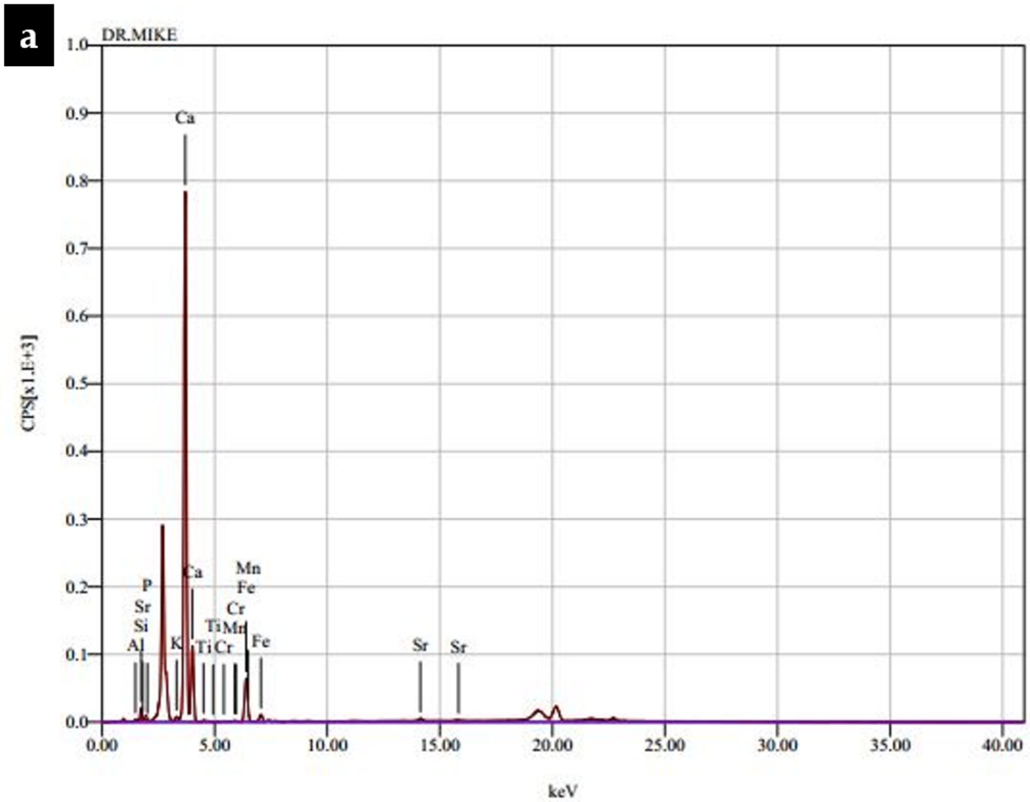


Figure 4.13: (a) Outcrop images showing the facies outcrop represented by wackestone beds interbedded with marls. (b) Zoomed in image showing some sedimentary features at the bed of sample. (c) (d) Thin section images of the samples showing muddy fabric with echinoderm fragments & some fracture and intergranular porosity in Em-w facies. (e) (f) SEM images showing the fine texture of the facies.



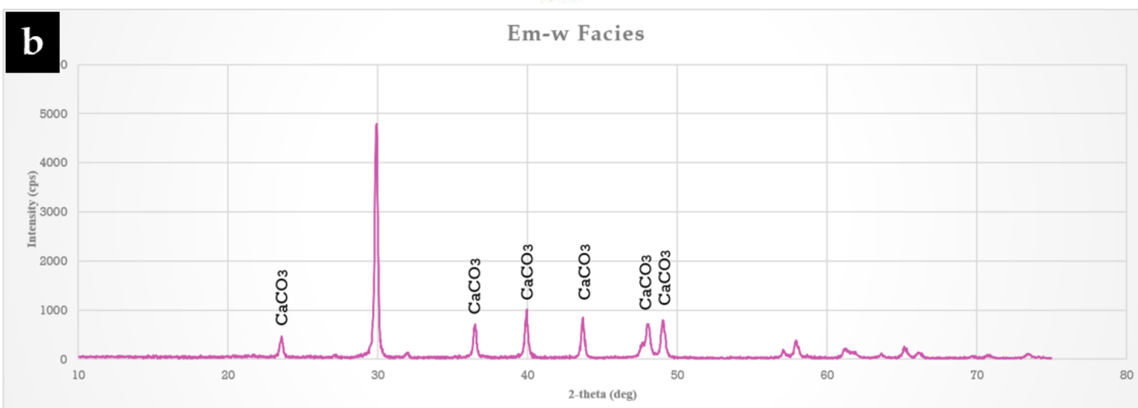


Figure 4.14: (a) XRF data showing the distribution of elements. (b) XRD results showing calcite as the major element with no traces of dolomite.

4.2.7 Bioclastic oolitic grainstone facies (Bog)

The bioclastic oolitic grainstone facies is mostly concentrated in the middle portion of the outcrop which represents the middle part of D5 member of Dhruma Formation. At the outcrop, the facies is composed of hard limestone beds of reddish yellow color which rusts to greenish on weathered surface. Some samples show small scale cross bedding but no other structures and features are seen (Figure 4.15 a, b). Seeing the thin sections, the facies is grainstone rich is bioclastic fragments of molluscs, corals, echinoderms, brachiopods and foraminifera. Non-skeletal grains include mostly ooids with some pelloids, pellets and intraclasts but oolites are the major non skeletal constituent consisting up to more than 50% in some samples (Figure 4.15 c, d).

The facies is highly cemented but internal structure of grains is preserved. Echinoderms and brachiopods are very clear and evident and are text book examples. Molluscs show internal micritization while some large bioclasts are highly preserved. Some grains are fused with each other and give rise to geopetal like structures. As most fragments are present haphazardly this indicates the high energy environment of deposition. Porosity is less evident but some intragranular and mouldic porosity is seen in some samples. Organic matter is not seen in this facies.

The major constituent of the facies is calcite as seen in XRD results (Figure 4.16 a, b). SEM images show some foraminifera and micrite cement with no other significant details to be observed (Figure 4.15 e, f).

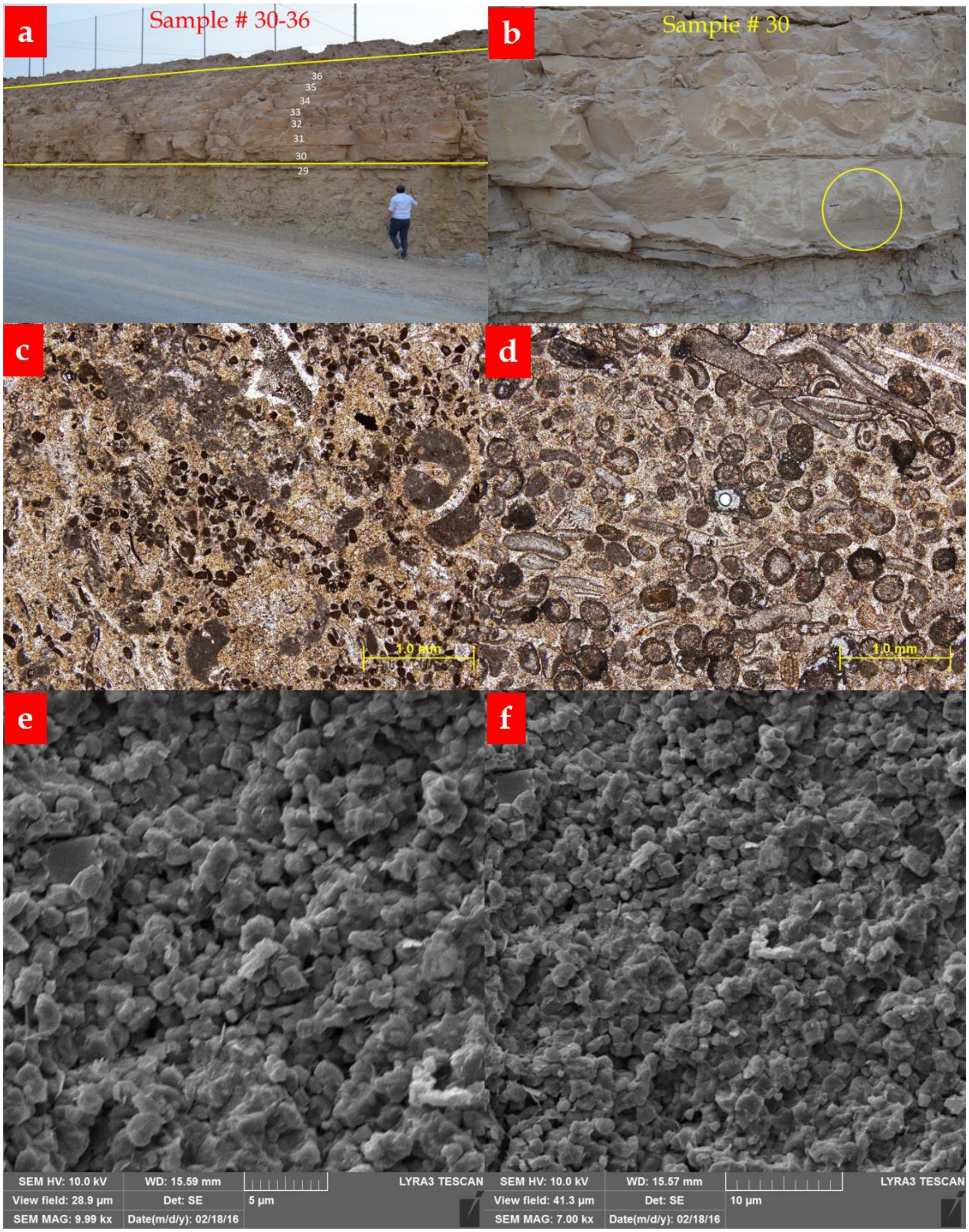


Figure 4.15: (a) Outcrop images showing the sample location. (b) Zoomed in image of the outcrop showing some sedimentary features present at the bed of sample. (c) (d) Thin section images of the samples showing mostly ooids along with other skeletal grains like corals, echinoderms & foraminifera in Bog facies. (e) (f) SEM images showing the micritic texture of facies.

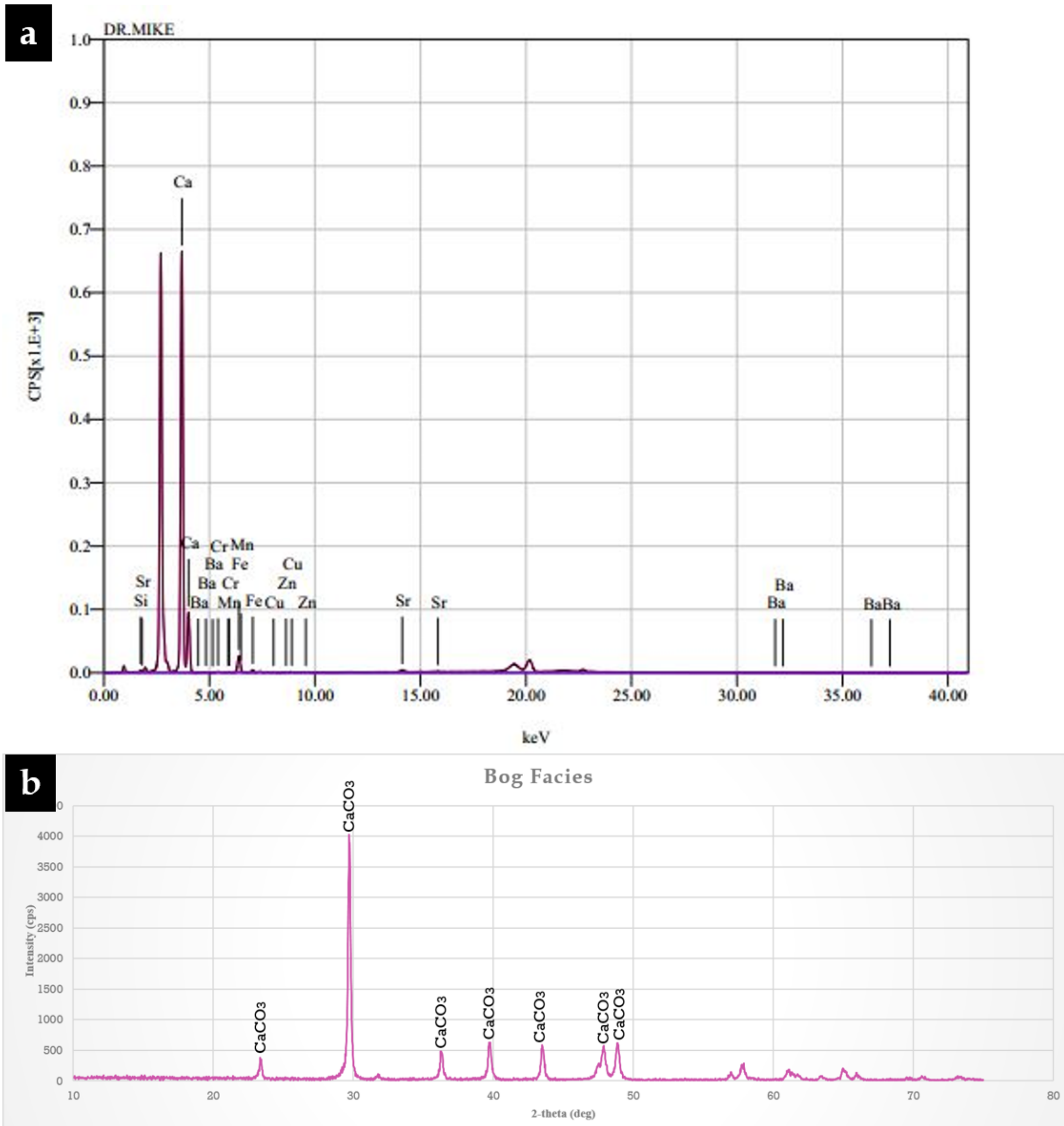


Figure 4.16: (a) XRF data showing the distribution of elements. (b) XRD results showing calcite as the major element with no traces of dolomite.

4.2.8 Foraminiferal wackestone facies (Fw)

Foraminiferal wackestone facies consists of mud rich samples which highly rich in foraminifera. In the outcrop, the facies is represented by friable limestone beds of medium thickness (Figure 4.17 a, b). In thin sections, along with forams, other skeletal grains are also present which include corals, bivalves, echinoderm fragments and sponge spicules. Non skeletal grains consists mainly pelloids of Mollusca (Figure 4.17 c, d). Samples are mostly muddy with pelloids showing diagenetic effects like replacement of grains. Porosity is not that evident in the samples and only fracture porosity is seen in a few.

SEM images show tight muddy texture with some foraminifera (Figure 4.17 e, f). No traces of dolomitization are seen in the thin sections which are latter confirmed by the lack of Mg mineral in XRF results. XRD analysis show mostly calcite as a major mineral occupying all peaks (Figure 4.18 a, b).

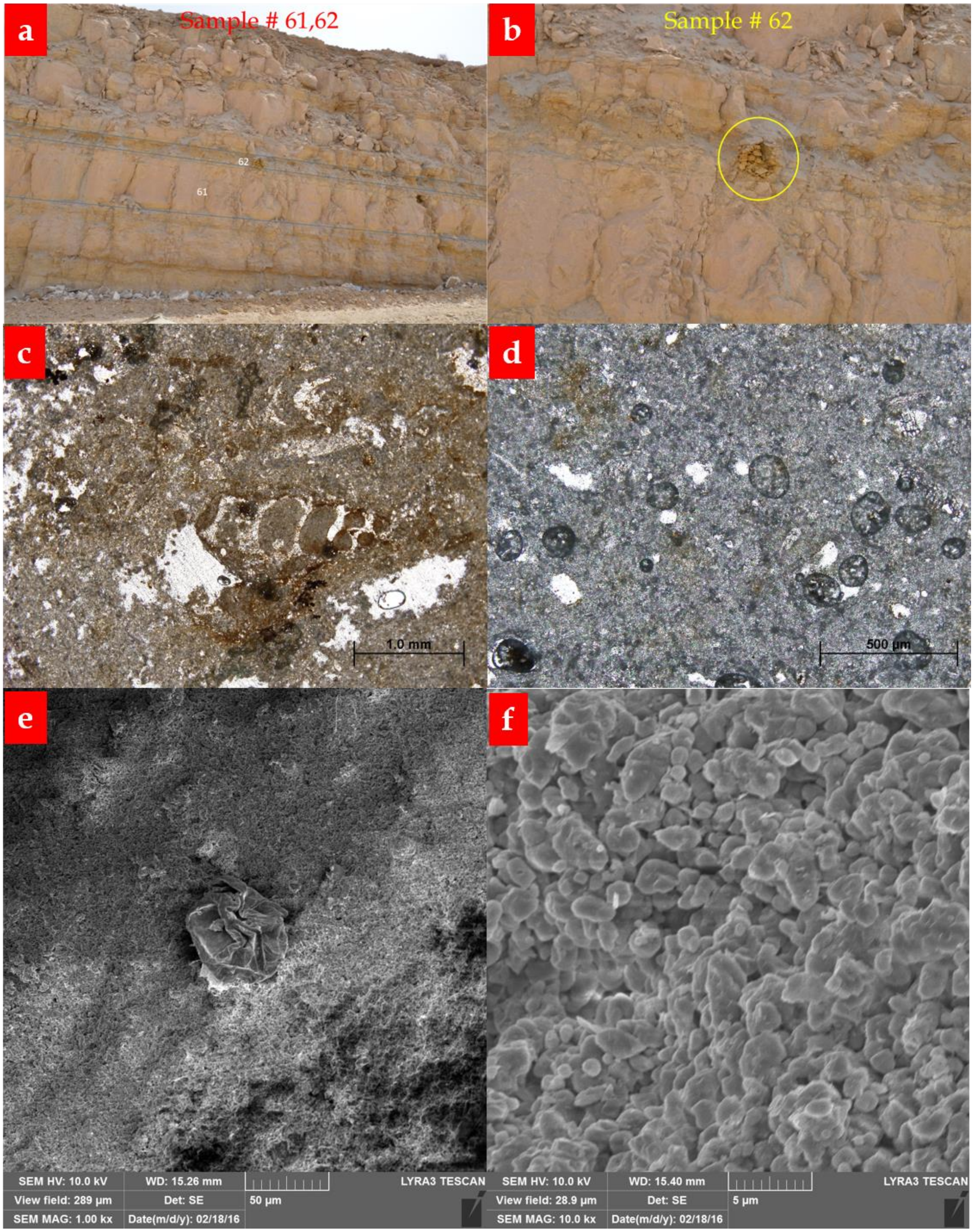


Figure 4.17: (a) Outcrop images showing the sample location interbedded in thick limestone layers. (b) Zoomed in image showing friable nature of sample with less obvious sedimentary features. (c) Thin section image showing foraminifera. (d) Thin section images of the samples showing abundant foraminifera distributed in muddy fabric Fw facies. (e) (f) SEM images showing the fine grained matrix of facies.

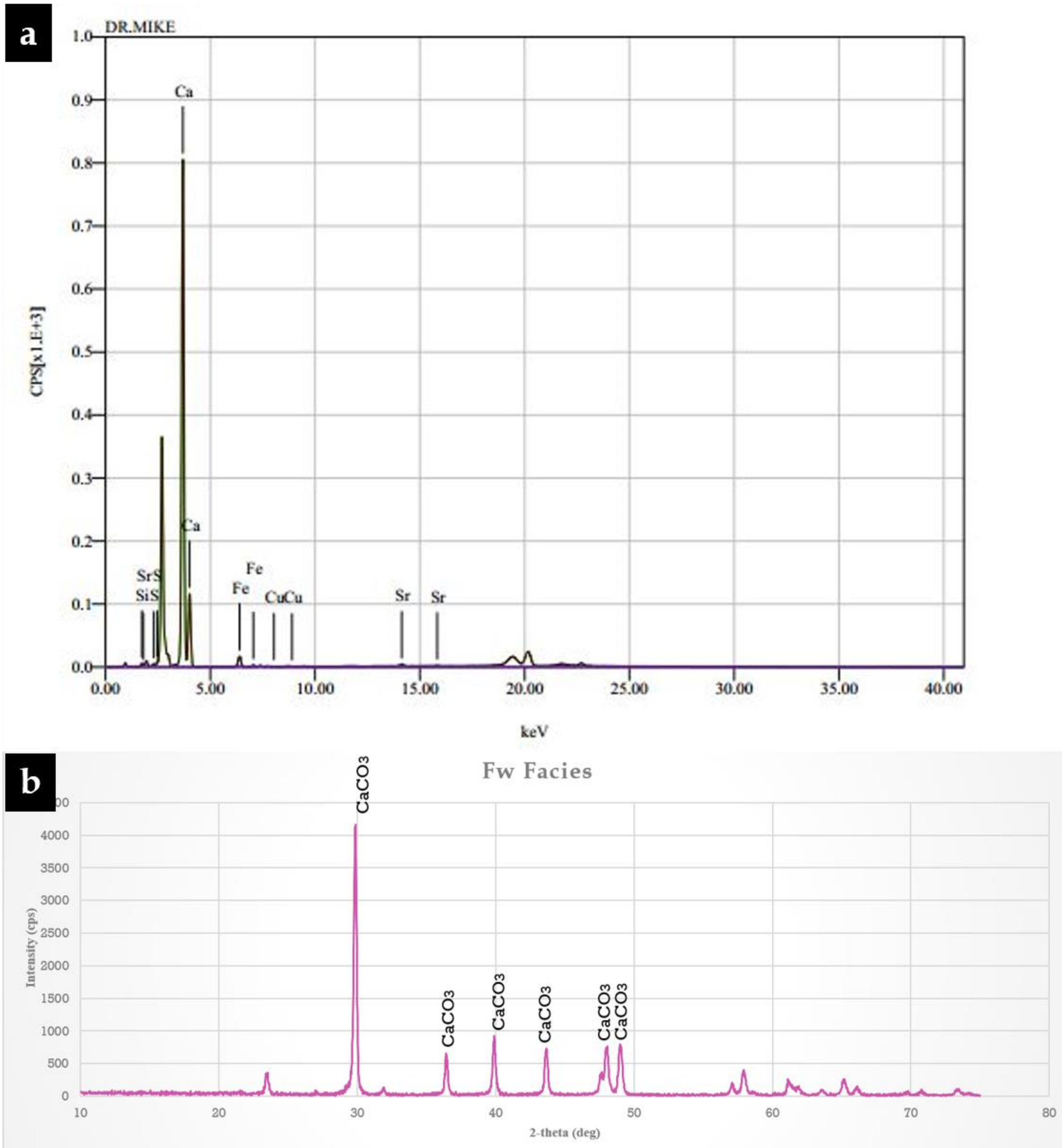


Figure 4.18: (a) XRF data showing the distribution of elements. (b) XRD results showing calcite as the major element with no traces of dolomite.

4.2.9 Spicule rich pelloidal grain dominated packstone facies (Spgdp)

The Spicule rich pelloidal grain dominated packstone facies is distributed throughout the outcrop and is encountered in lower, middle and upper parts. In the outcrop facies consists of light colored hard limestone beds which rust to reddish brown on weathered surface. Limestones are channelized with some fine grained pebbles and quartz fragments with small scale cross bedding and some horizontal laminations (Figure 4.19 a, b). In thin sections, the facies is grainy and has spicules as major skeletal fragments. Along with spicules, broken echinoderm fragments, foraminifera and bivalves are also present. Non-skeletal grains are dominated by pelloids with some ooids. In some samples fabric is that evident due to micritization of grains. Mud is present in some areas but grains are abundant elsewhere (Figure 4.19 c, d). Organic matter is also present in few samples.

SEM images of the facies show calcite crystals in fine matrix (Figure 4.19 e, f). No valid evidence of dolomitization is seen XRD analysis also show calcite as major mineral. Mg is not found in XRF and Si, Fe Mn, and Cr are present in small quantities with Ca which is the major element (Figure 4.20 a, b).

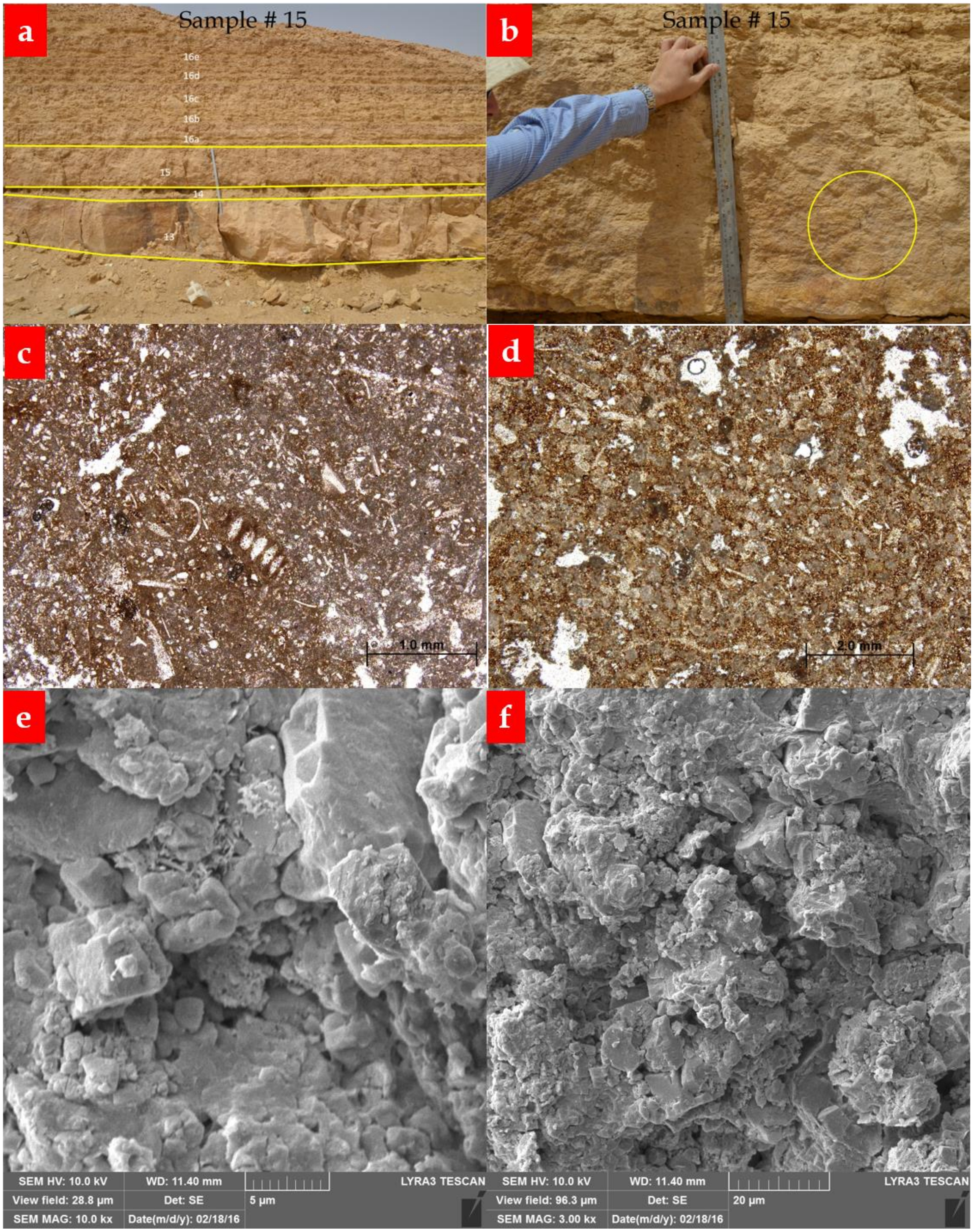


Figure 4.19: (a) Outcrop images showing the sample location as thick limestone beds. (b) Zoomed in image showing some sedimentary features at the bed surface. (c) (d) Thin section images of the samples showing rich spicules along with pelloids, some foraminifera & other skeletal grains. (e) (f) SEM images showing the texture of facies.

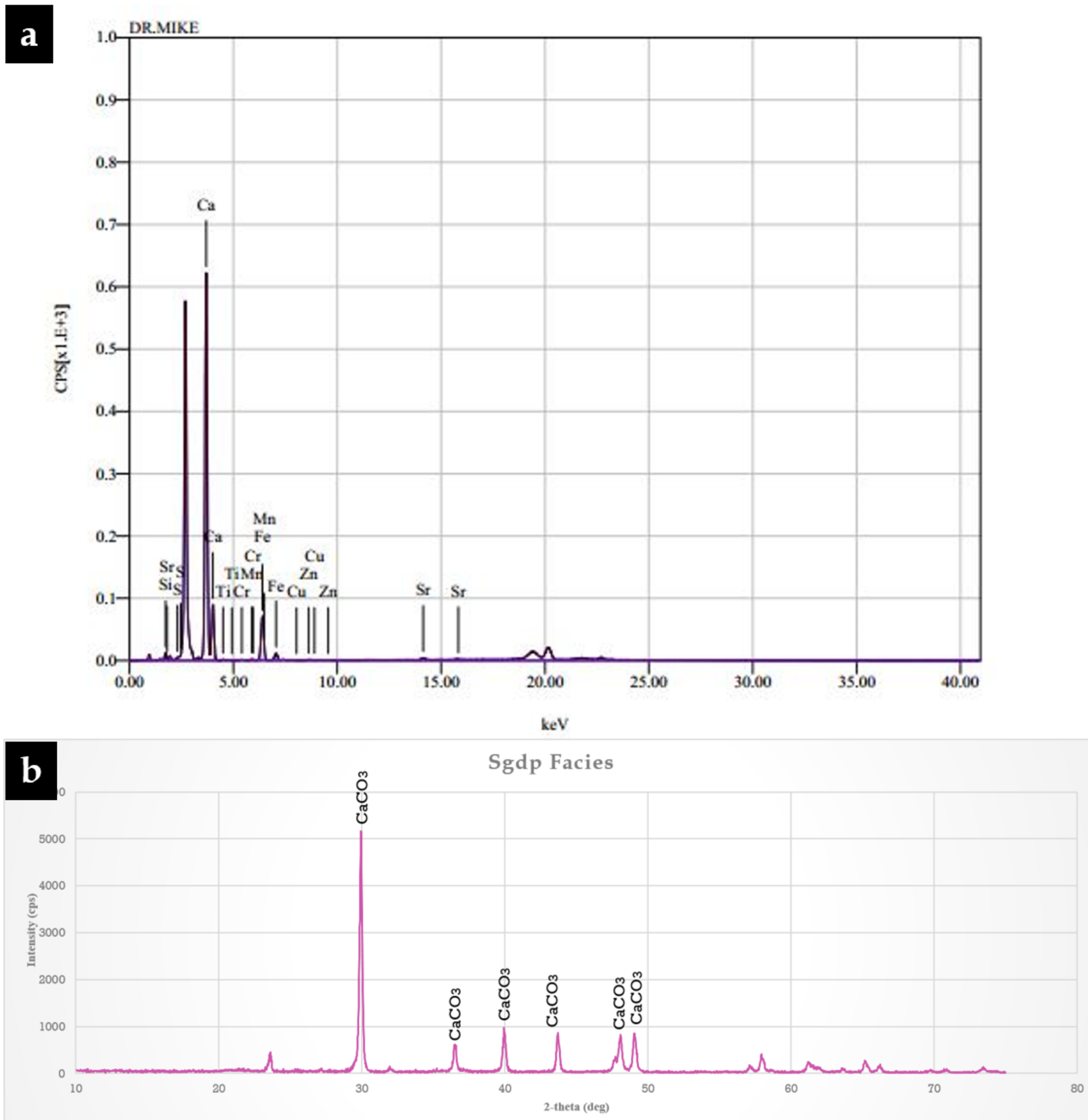


Figure 4.20: (a) XRF data showing the distribution of elements. (b) XRD results showing calcite as the major element with no traces of dolomite.

4.2.10 Mudstone Facies (Ms)

Mudstone facies is the most abundant facies throughout the outcrop showing high quantities of muds. In the outcrop Mudstone facies is represented by either friable lime-mudstones which break with concoidal fractures or by marly beds present in-between the limestones. Thick Marls are present in the lower and upper part while middle portions contain mudstones interbedded in thick limestone layers. Thin sections are very difficult to made from these samples as they dissolve when come in contact with water (Figure 4.21 a, b, c, d).

The samples are washed for microfossil studies and specimens are collected. Study of microfossils shows presence of different species of foraminifera along with ostracods, gastropods, echinoderm fragments and sponge spicules. Scanning electron microscope data yields calcite grains present in fine grained matrix with no other recognizable features (Figure 4.21 e, f). XRD results also show calcite as major mineral occupying all major peaks. XRF data also show abundance of Calcium with minute traces of Fe, Mn, Si, K, Al and Zn (Figure 4.22 a, b).

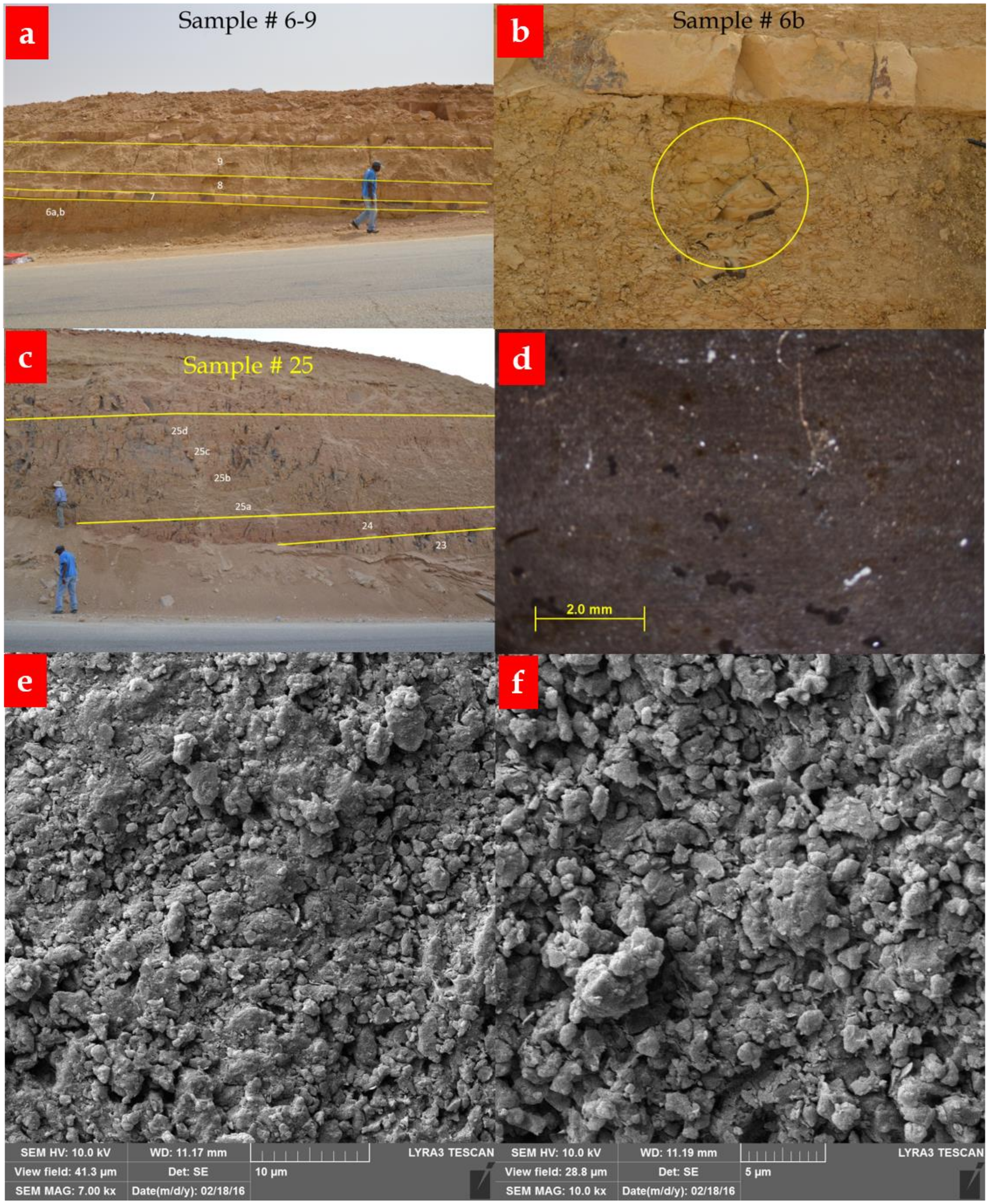


Figure 4.21: (a)(c) Outcrop images showing the sample location as thick bedded reddish nodular muds which breaks easily. (b) Zoomed in image showing friable nature of samples with less evident sedimentary features. (d) Thin section images of the samples are very difficult to make and doesn't show any details of Ms facies. (e) (f) SEM images showing the fine texture of the facies.

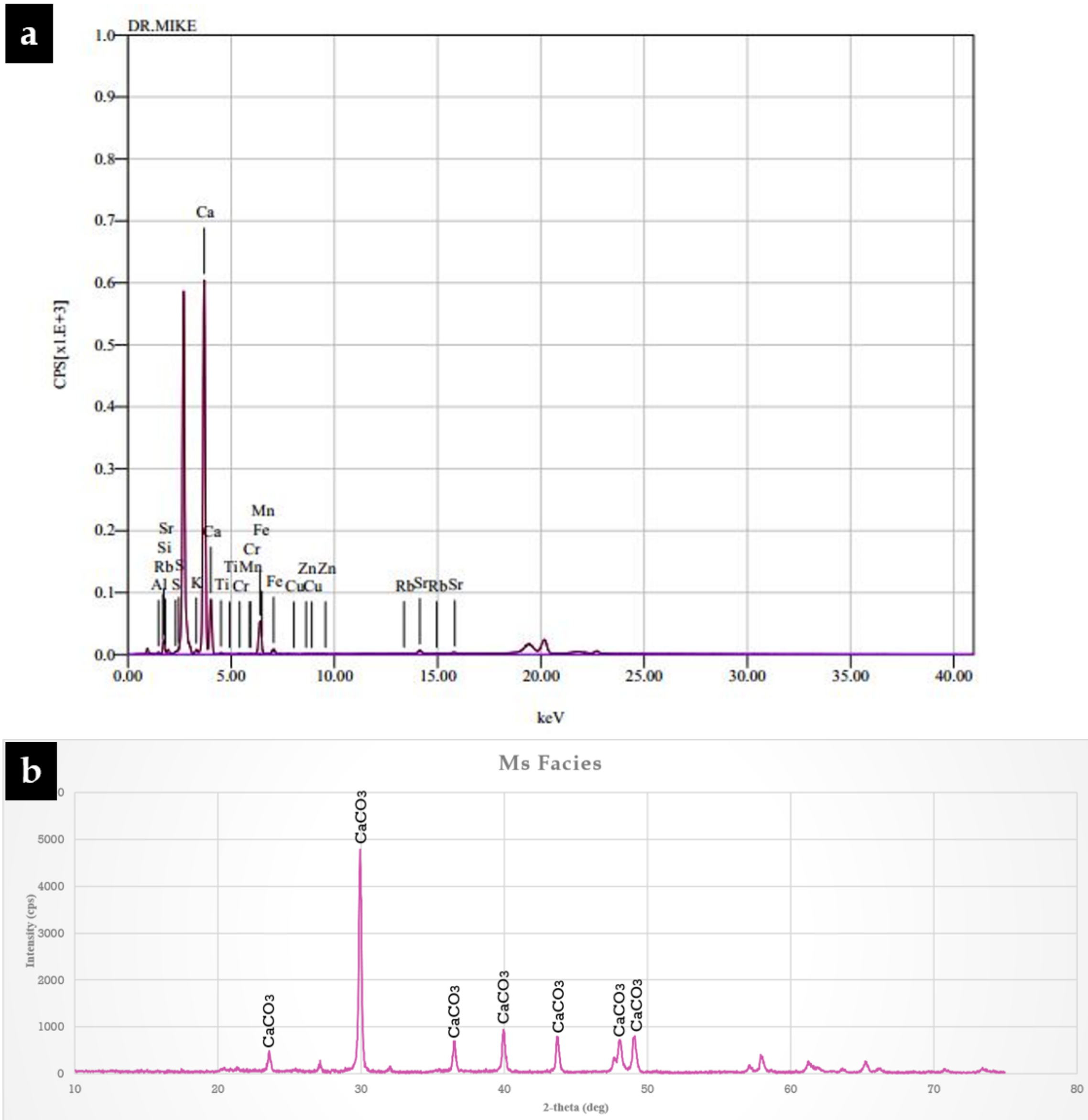


Figure 4.22: (a) XRF data showing the distribution of elements. (b) XRD results showing calcite as the major element with no traces of dolomite.

CHAPTER 5

RESULTS

MICROPALEONTOLOGY

5.1 Introduction

This chapter gives the details about the microfossil taxonomy, specifically the foraminifera identified within the middle members of the Middle Jurassic Dhruma Formation. This study examines the physically extracted fossils from acid residues. The physically extracted foraminifera give us the benefit of well-pronounced details and easy identification to the species level in many cases. As for other aspects of this study the outcrop was subdivided into different lithofacies, and microfossil identification has been carried out based on their occurrences in these lithofacies. However, care has been taken for the equal distribution of picked samples throughout the stratigraphic column. A total of 35 foraminiferal species were identified belonging to 19 genera. The occurrences are plotted separately in the discussion chapter showing the distribution of species in the samples. This enables us to recognize the vertical variations and hence any relationship with the changing sea level and sequences. This chapter reports the identified foraminifera species within each lithofacies.

5.2 Extracted Microfossil Genera & Species

From the samples taken from middle part of Dhruma Formation, 19 different genera of foraminifera have been extracted and identified. These genera are then further identified to the species level and 38 species have been recorded and photographed. Some of samples are difficult to be identified to the species level, and were left for the time being for further identification. The genera along with their species are given below in the list while their details are given in systematics section.

Genus *Andersenolina* Neagu, 1994

1. *Andersenolina alpina (*Leupold, 1936)
2. *Andersenolina elongata* (Leupold, 1936)

Genus *Everticyclammina* Redmond, 1964

3. *Everticyclammina contorta* Redmond, 1964

Genus *Kurnubia* Henson, 1948

4. *Kurnubia bramkampi* Redmond, 1964
5. *Kurnubia variabilis* Redmond, 1964

Genus *Lenticulina* Lamarck, 1804

6. *Lenticulina* sp. 1-10

Genus *Lingulina* d'Orbigny, 1826

7. *Lingulina sp.*

Genus *Nautiloculina* Mohler, 1938

8. *Nautiloculina* sp. 1-2

Genus *Nodosaria* Lamarck, 1812

9. *Nodosaria fontinensis* Terquem, 1870

10. *Nodosaria* sp. 1, 2

Genus *Pfenderina* Henson, 1948

11. Pfenderina gracilis Redmond, 1964

12. Pfenderina inflata Redmond, 1964

13. *Pfenderina* sp. 1, 2

Genus *Polymorphina* d'Orbigny, 1826

14. *Polymorphina* sp. 1-5

Genus *Posadia* Guisberti & Coccioni 2003

15. *Posadia* sp. 1

Genus *Pseudomarssonella* Redmond, 1965

16. *Pseudomarssonella* sp. 1

Genus *Pseudonodosaria* Boomgaart, 1949

17. Pseudonodosaria hybrida (Turquem & Berthelin, 1875)

18. Pseudonodosaria vulgata (Borneman, 1854)

Genus *Rashnovammina* Neagu & Neagu, 1995

19. Rashnovammina carpathica Neagu & Neagu, 1995

Genus *Redmondoides* Banner, Simmons and Whittaker, 1991

20. Redmondoides inflatus (Redmond, 1964)

21. *Redmondoides lugeoni* (Septfontaine, 1977)

22. Redmondoides media (Redmond, 1964)

23. Redmondoides primitivus (Redmond, 1964)

24. Redmondoides rotundatus (Redmond, 1964)

25. *Redmondoides* sp. 1, 2, 3

Genus *Riyadhella* Redmond, 1965

26. Riyadhella arabica Redmond, 1965

27. Riyadhella elongata Redmond, 1965

28. Riyadhella inflata Redmond, 1965

29. Riyadhella regularis Redmond, 1965

30. *Riyadhella* sp. 1, 2

Genus *Riyadhoides* Banner, Simmons & Whittaker, 1991

31. Riyadhoides mcclurei (Redmond, 1965)

Genus *Siphovalvulina* Septfontaine, 1988

32. *Siphovalvulina* sp. 1-8,

Genus *Spirillina* Ehrenberg, 1843

33. Spirillina polygyrata Guembel, 1862

34. *Spirillina* sp. 1

Genus *Steinekella* Redmond, 1964

35. Steinekella steinekei Redmond, 1964

5.3 Microfossil Genera & Species distribution:

5.3.1 Coral bearing grain dominated Packstone Facies (Cgdp)

The total number of foraminifera species identified in the coral bearing grain dominated packstone facies are about 13 belonging to 9 different genera. Along with them some unidentified species are also present which are not mentioned. These includes species of gastropods, ostracods etc. The identified species and their percentage distributions in representative samples are given as under in Table 5.1. Representative specimens from the facies are shown in Plates 5.1, 5.2 & 5.3.

Table 5.1: Foraminifera species and their % distribution in samples of coral bearing grain dominated packstone facies.

Species / **Sample No.**	***Riyadhella regularis***	***Riyadhella inflata***	***Redmondoides inflatus***	***Redmondoides media***	***Redmondoides rotundatus***	***Redmondoides primitivus***	***Siphovalvulina* sp.**	***Spirillina* sp.**	***Lenticulina* sp.**	***Polymorphina* sp.**	***Pseudonodosaria hybrida***	***Pfenderina* sp.**	***Nautiloculina* sp.**
16D (%)	6	--	23	17	5.3	--	--	2	8.6	--	--	--	--
38 (%)	8	28	21	2.5	20	--	3	--	2.3	2.3	1	--	--
54 (%)	15	3	15	--	24	7	--	2.5	--	--	--	20	9.5
56 (%)	15	3	19	13	--	17	1.5	--	5	3.5	0.5	3	6.5

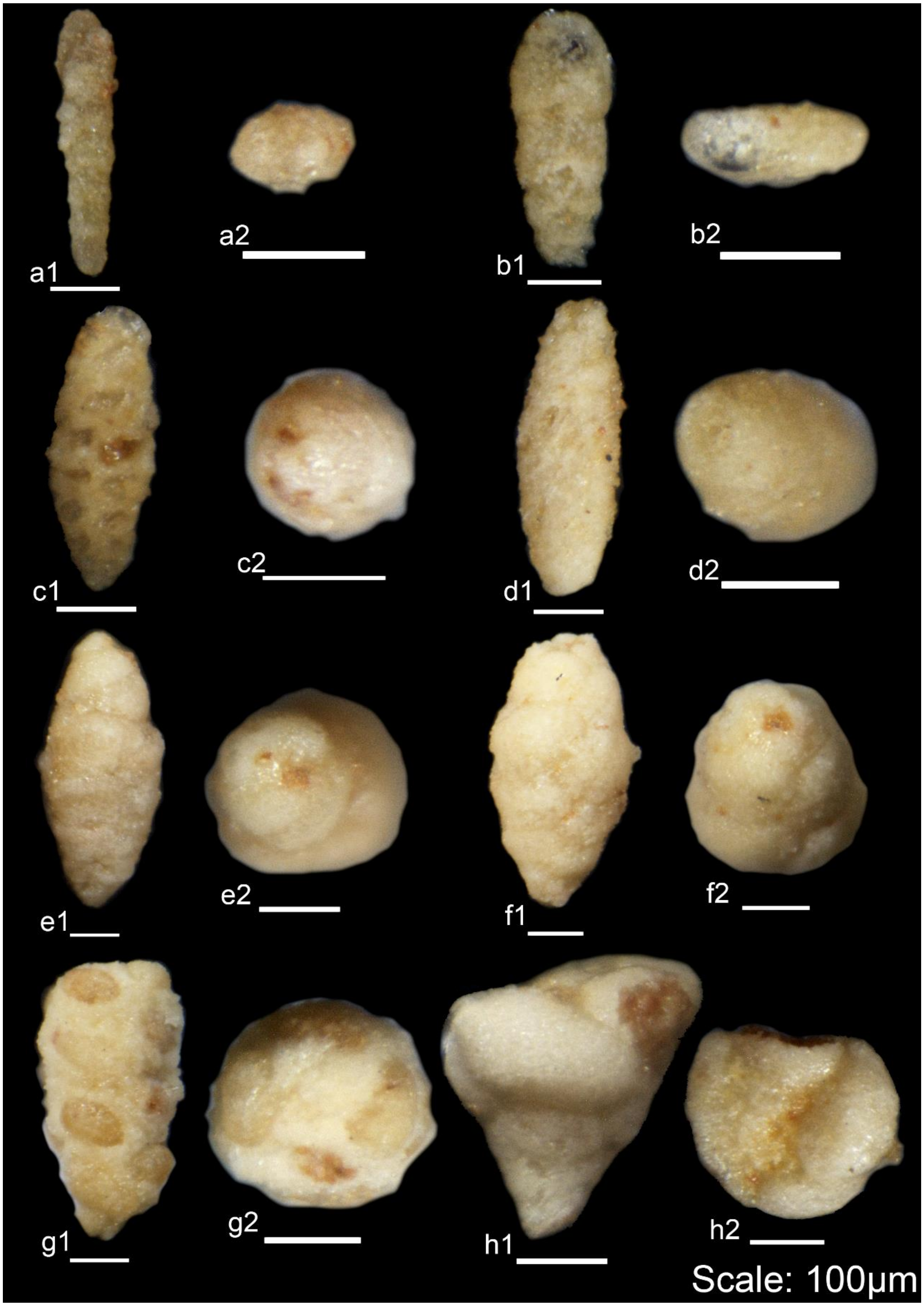


Plate 5.1. A. *Pseudonodosaria hybrida,* Sample 38. **B.** *Lingulina sp.* Sample 38. **C, D.** *Riyadhella regularis* Sample 38. **E, F.** *Riyadhella inflata,* Sample 38. **G**. Redmondoides rotundatus, Sample 38. **H.** Redmondoides inflatus, Sample 38.

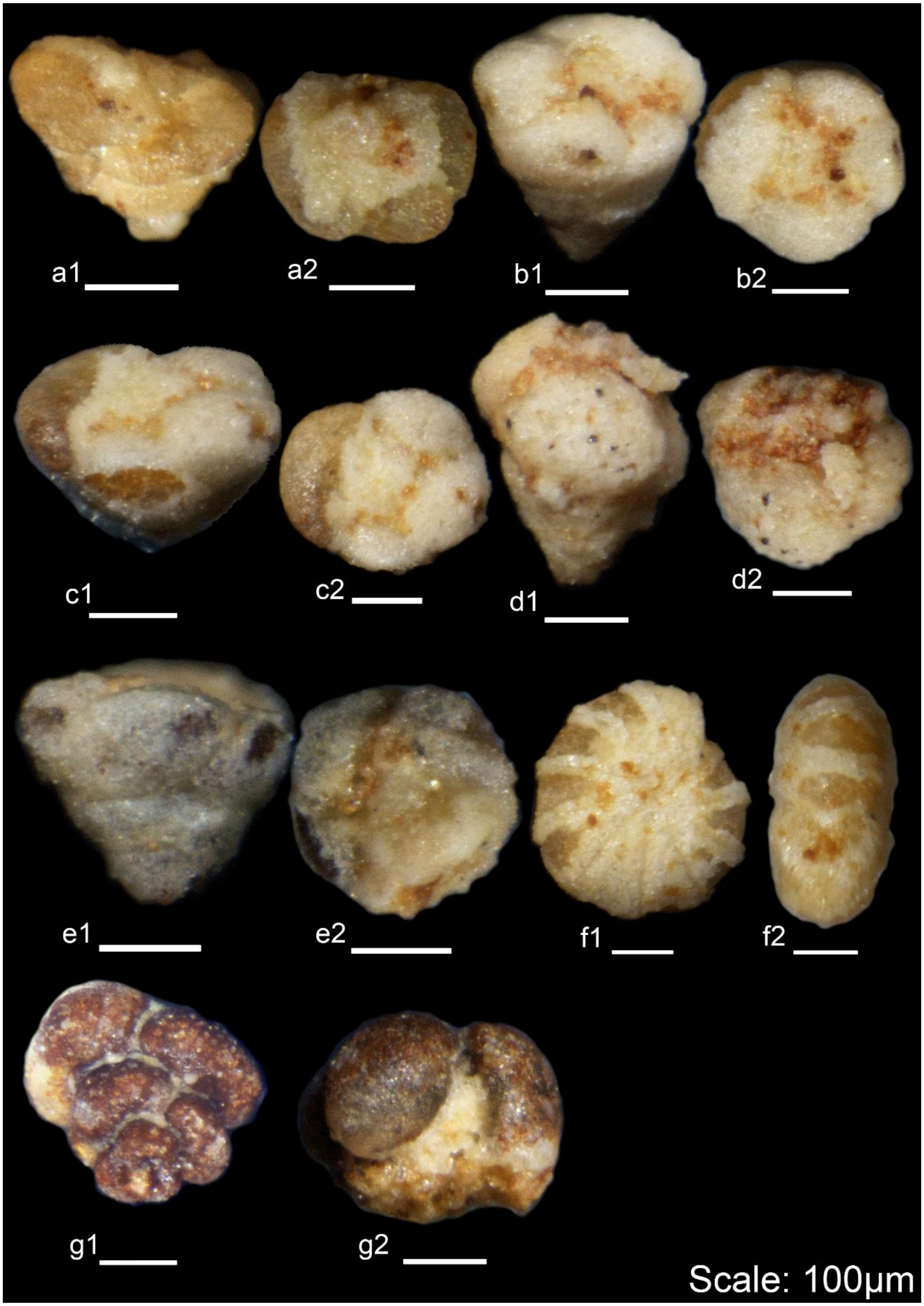


Plate 5.2. A, B, C, E. *Redmondoides inflatus,* Sample 38. **D.** *Redmondoides rotundatus,* Sample 38. **F.** *Lenticulina* sp. 1, Sample 38. **G**. *Siphovalvulina* sp. 1, Sample 38.

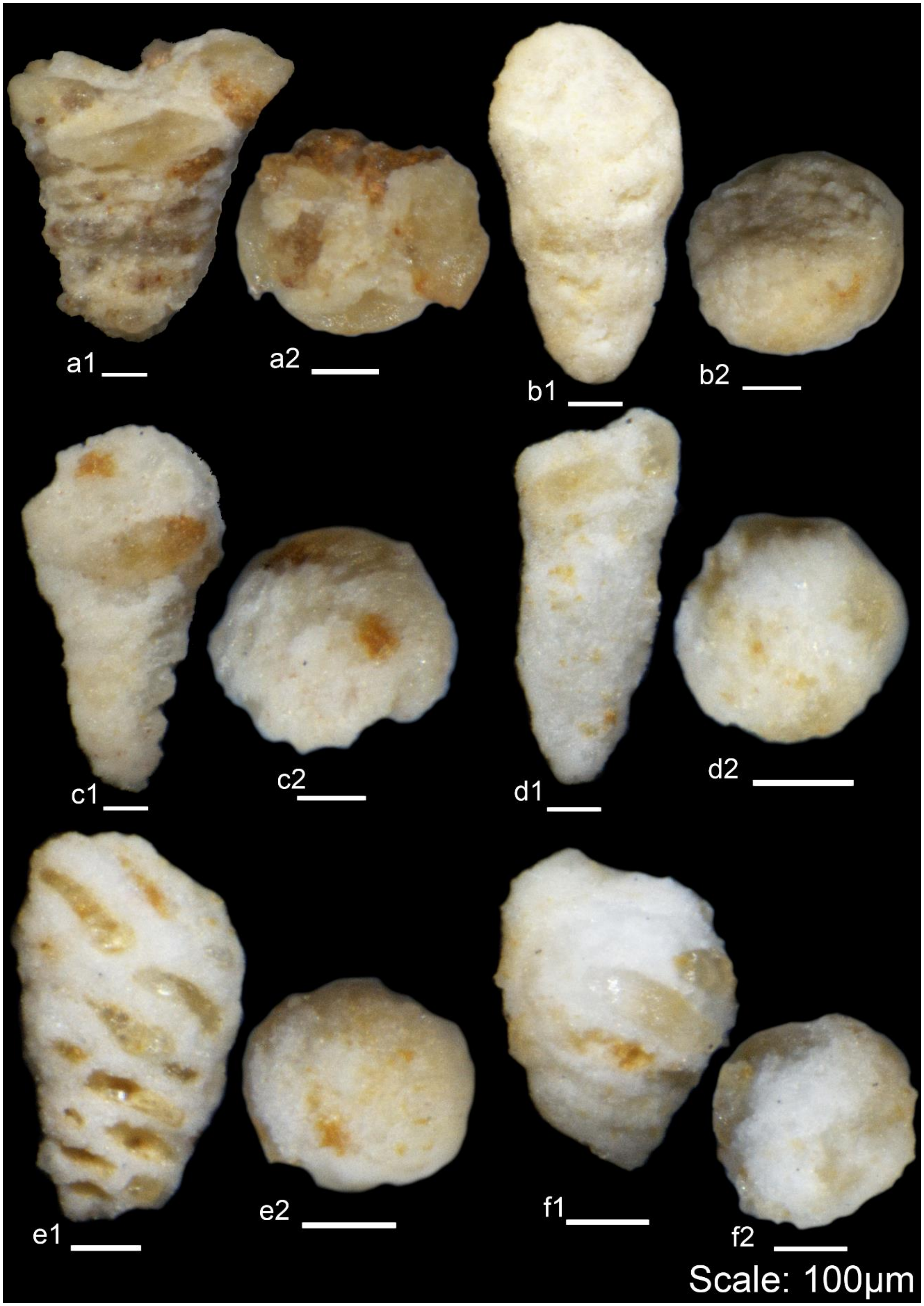


Plate 5.3. A. *Redmondoides media*, Sample 56. **B.** *Riyadhella arabica*, Sample 56. **C, D.** *Redmondoides primitivus*, Sample 56, 54. **E.** *Pfenderina* sp.1, Sample 54. **F.** *Pfenderina* sp. 2, Sample 54.

5.3.2 Echinoderm Spiculitic Packstone Facies (Esp)

In the echinoderm spiculitic packstone facies, we have identified about 10 species belonging to 6 genera. These species and their percentage distributions in representative samples are given as under in Table 5.2. Representative specimens from the facies are shown in Plates 5.4 & 5.5.

Table 5.2: Foraminifera species and their % distribution in samples of echinoderm spiculitic packstone facies.

Species / Sample No.	*Riyadhella regularis*	*Riyadhella* sp.	*Redmondoides inflatus*	*Redmondoides media*	*Redmondoides rotundatus*	*Redmondoides primitivus*	*Spirillina polygyrata*	*Lenticulina* sp.	*Polymorphina* sp.	*Nautiloculina* sp.
02A (%)	6	--	33.3	2.6	2	20	--	2.6	2	9.3
16E (%)	1.3	6.6	25	6.6	16.6	--	6.6	11.3	--	6.6

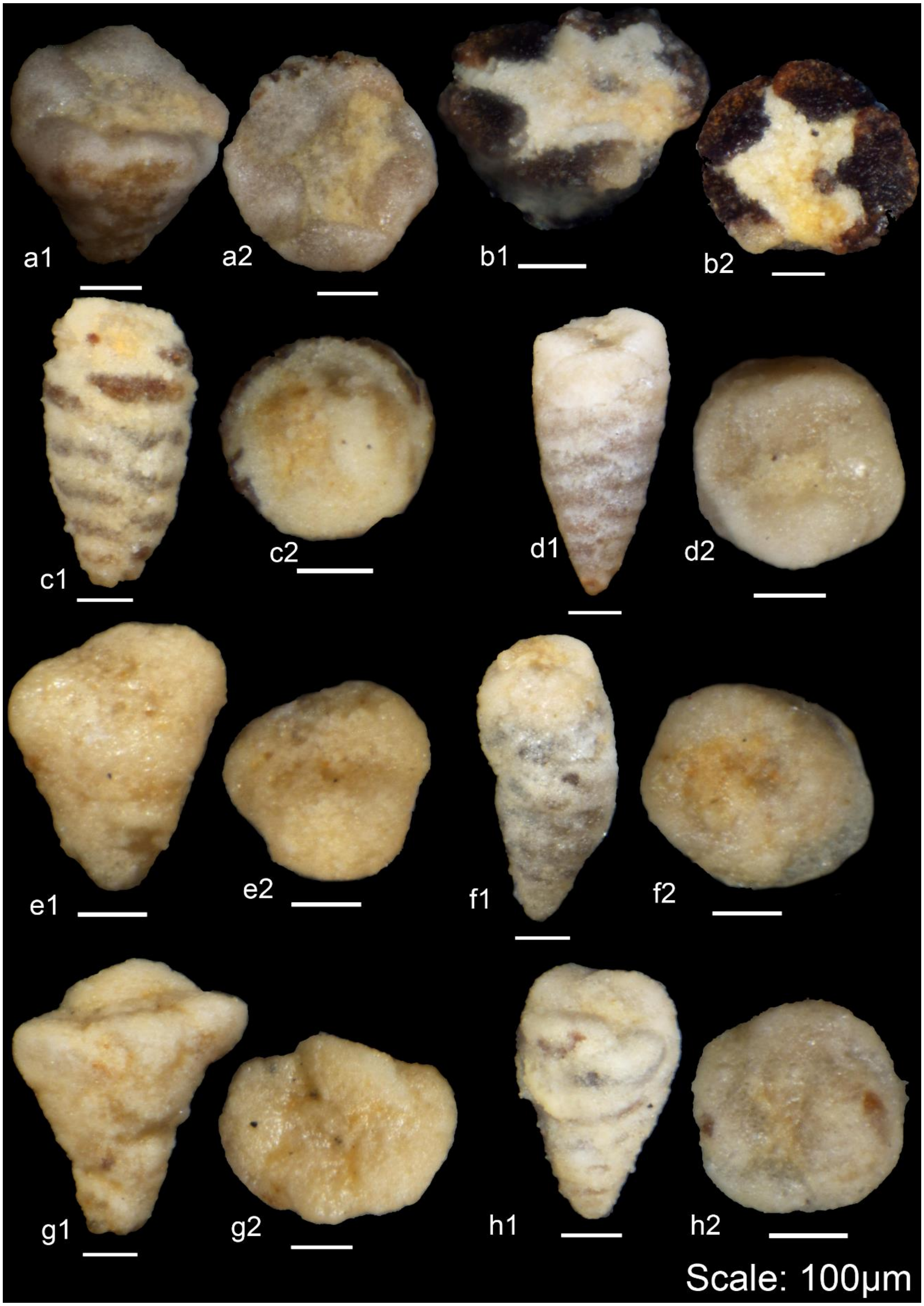


Plate 5.4. A, B. *Redmondoides inflatus,* Sample 02A. **C, D.** *Redmondoides primitivus,* Sample 02A. **E, F.** *Redmondoides rotundatus,* Sample 16E. **F.** *Riyadhella rotundatus,* Sample 02A. **G, H.** *Redmondoides media,* Sample 16E.

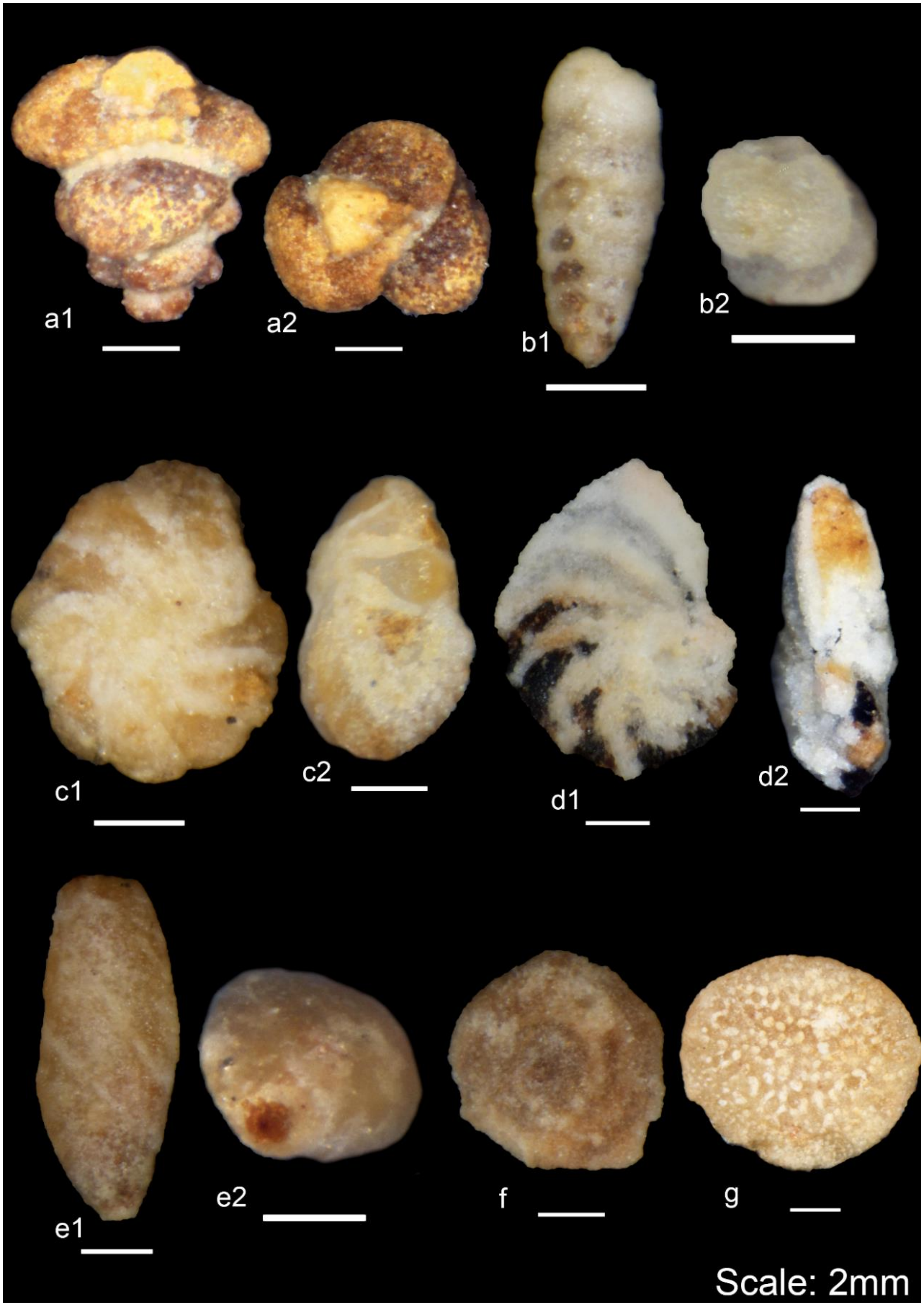


Plate 5.5. A. *Siphovalvulina* sp. 2, Sample 02A. **B.** *Riyadhella regularis,* Sample 16E. **C.** *Nautiloculina* sp. 1, Sample 16E. **D.** *Lenticulina* sp. 1, Sample 02A. **E.** *Polymorphina* sp. 1, Sample 02A. **F.** *Spirillina polygyrata*, Sample 16E. **G. 16E**

5.3.3 Oolitic Grainstone facies (Og)

The total number of species identified in the oolitic grainstone facies are about 9 which belong to7 different genera. The recovery from the facies is relatively low due to its dominant grain content. The sample 28 belongs to a resistive layer and has very low recovery while for sample 34 recovery is better. The identified species and their percentage distributions in representative samples are given as under in Table 5.3. Representative specimens from the facies are shown in Plates 5.6 & 5.7.

Table 5.3: Foraminifera species and their % distribution in samples of oolitic grainstone facies.

Species / Sample No.	*Riyadhella regularis*	*Riyadhella inflata*	*Redmondoides inflatus*	*Redmondoides media*	*Siphovalvulina* sp.	*Nodosaria fontinensis*	*Lenticulina* sp.	*Polymorphina* sp.	*Nautiloculina* sp.
28 (%)	--	--	--	--	--	4	--	60	--
34 (%)	20	6.6	8	3.3	10	--	3.3	--	10

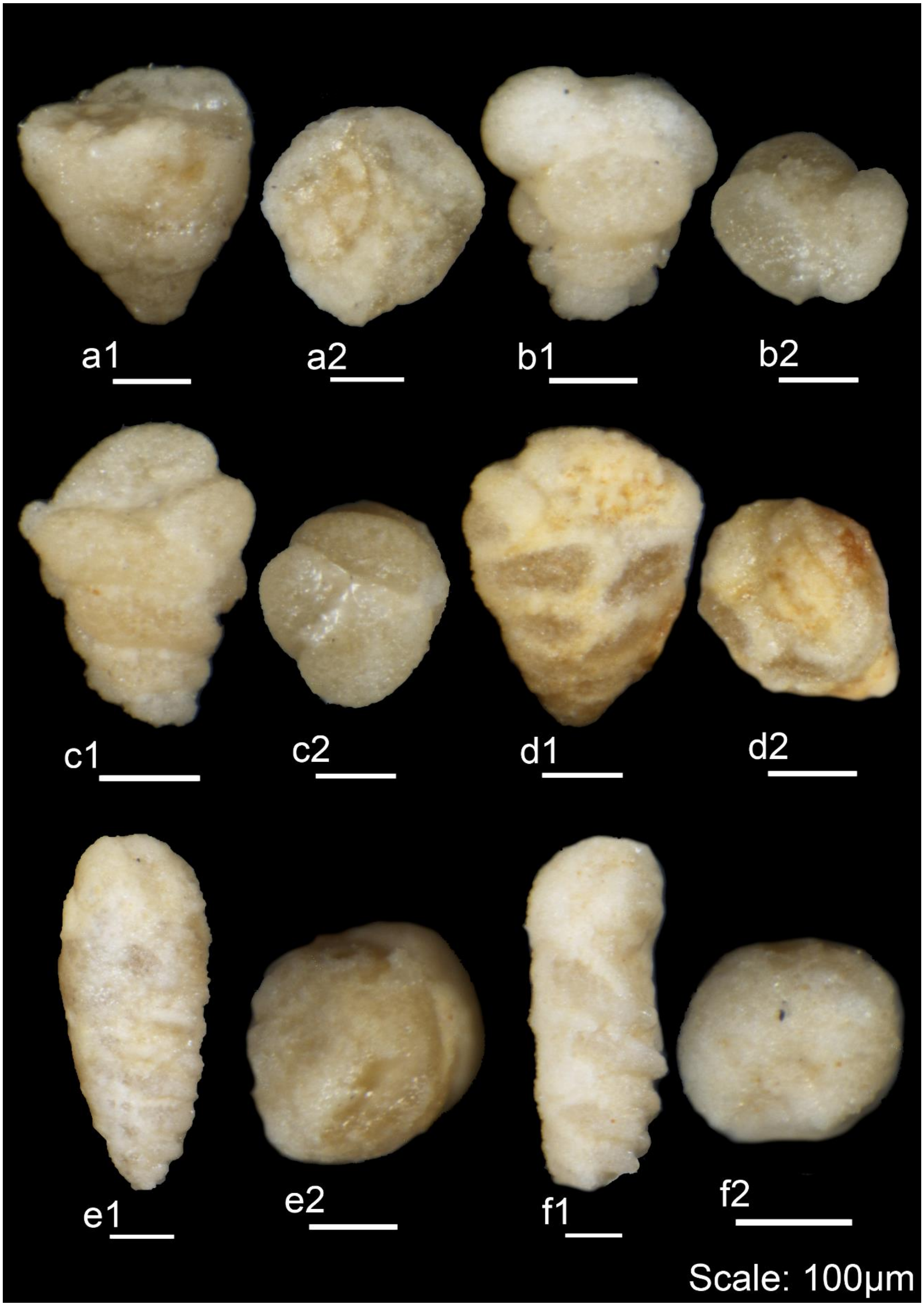


Plate 5.6. A. *Redmondoides inflatus*, Sample 34. **B.** *Siphovalvulina* sp. 2**,** Sample 34. **C.** *Siphovalvulina* sp. 3, Sample 34. **D.** *Redmondoides media,* Sample 34. **E, F.** *Riyadhella regularis,* Sample 34.

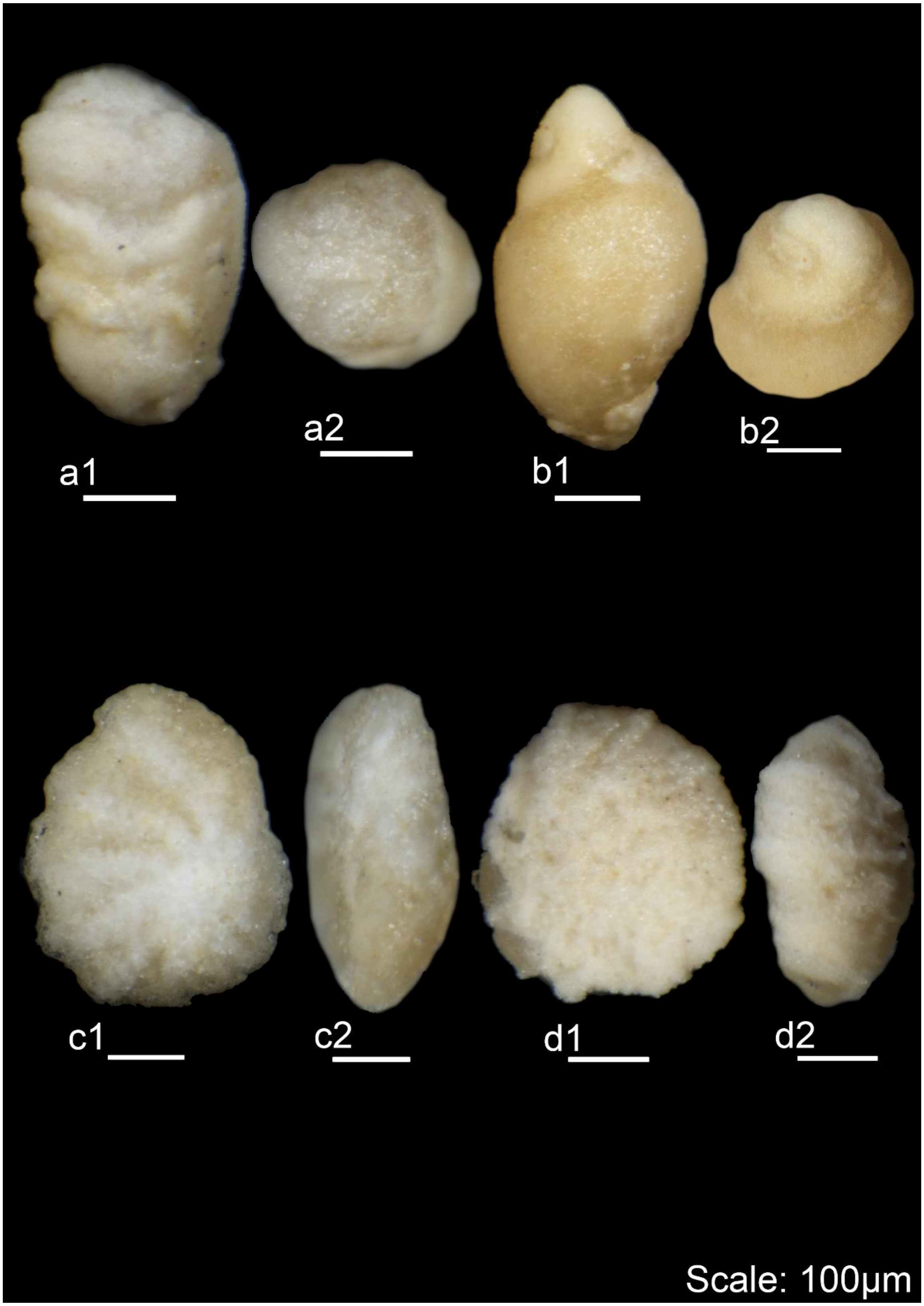


Plate 5.7. A. *Riyadhella inflata,* Sample 34. **B.** *Steinekella steinekei,* Sample 34. **C.** *Lenticulina* sp. 2, Sample 34. **D.** *Lenticulina* sp. 3, Sample 34**.**

5.3.4 Bioclastic Wackestone / Packstone Facies (Bw-p)

The total number of foraminifera species identified in the bioclastic wackestone to packstone facies are about 11 belonging to7 different genera. The fossil recovery from the facies is fairly good with samples rich in fossils. For sample 60 however, size of fossils is relatively small and there are no gastropods or ostracods present. The identified species along with their percentage distribution in samples are given in Table 5.4. Representative specimens from the facies are shown in Plate 5.8.

Table 5.4: Foraminifera species and their % distribution in samples of bioclastic wackestone / packstone facies.

Species / **Sample No.**	***Riyadhella regularis***	***Riyadhella inflata***	***Riyadhella* sp.**	***Redmondoides inflatus***	***Redmondoides rotundatus***	***Siphovalvulina* sp.**	***Lenticulina* sp.**	***Polymorphina* sp.**	***Pfenderina inflatus***	***Pfenderina gracilis***	***Nautiloculina* sp.**
48 (%)	40	10	15	8	3	3	1.5	1	--	--	--
60 (%)	5	3.3	1.6	8.3	5	6.6	17.3	1.3	5.6	3.3	15

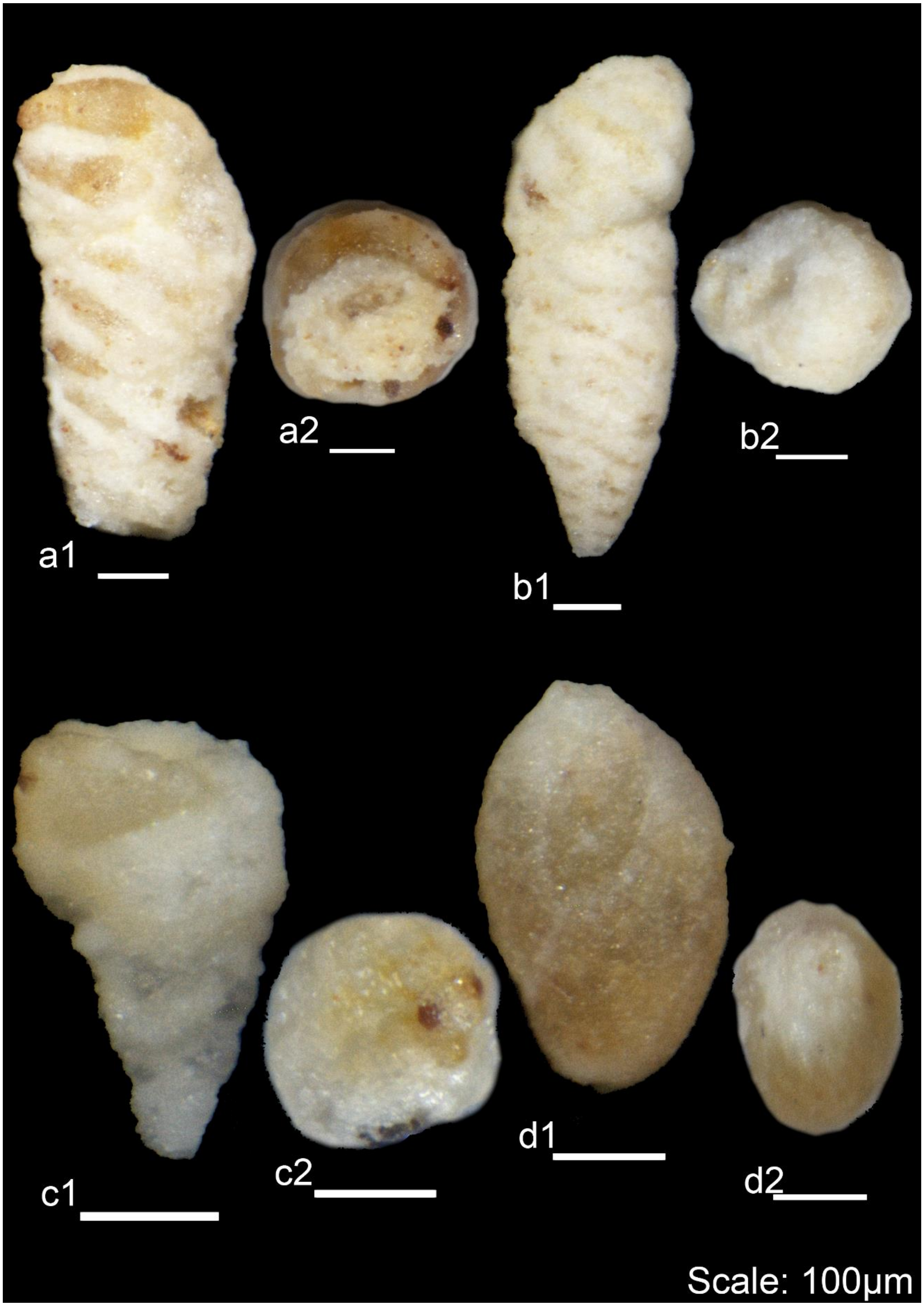


Plate 5.8. A. *Pfenderina inflata*, Sample 60. **B.** *Pfenderina gracilis,* Sample 60. **C.** *Redmondoides media,* Sample 60. **D.** Polymorphina sp. 2, Sample 60.

5.3.5 Foraminiferal Packstone / Grainstone Facies (Fp-g)

The total number of foraminifera species identified in the foraminiferal packstone to grainstone facies are about 13 belonging to 8 different genera. The facies show random abundance with sample 49 showing very less recovery while sample 65 showing abundant recovery with some very small and some very large size fossils. The identified species with their percentage distribution in samples are given in Table 5.5. Representative specimens from the facies are shown in Plate 5.9.

Table 5.5: Foraminifera species and their % distribution in samples of foraminiferal packstone / grainstone facies.

Species / Sample No.	*Riyadhella regularis*	*Riyadhella inflata*	*Riyadhella arabica*	*Redmondoides inflatus*	*Redmondoides media*	*Redmondoides rotundatus*	*Andersenolina alpina*	*Andersenolina elongata*	*Siphovalvulina* sp.	*Lenticulina* sp.	*Polymorphina* sp.	*Posadia* sp.	*Nautiloculina* sp.
45 (%)	4	--	--	38	21	--	--	--	3.3	3.3	--	--	--
49 (%)	5	--	--	--	15	--	--	--	--	5	--	--	--
65 (%)	12	4	5	4	22	15	5	5	--	2	2	2	8

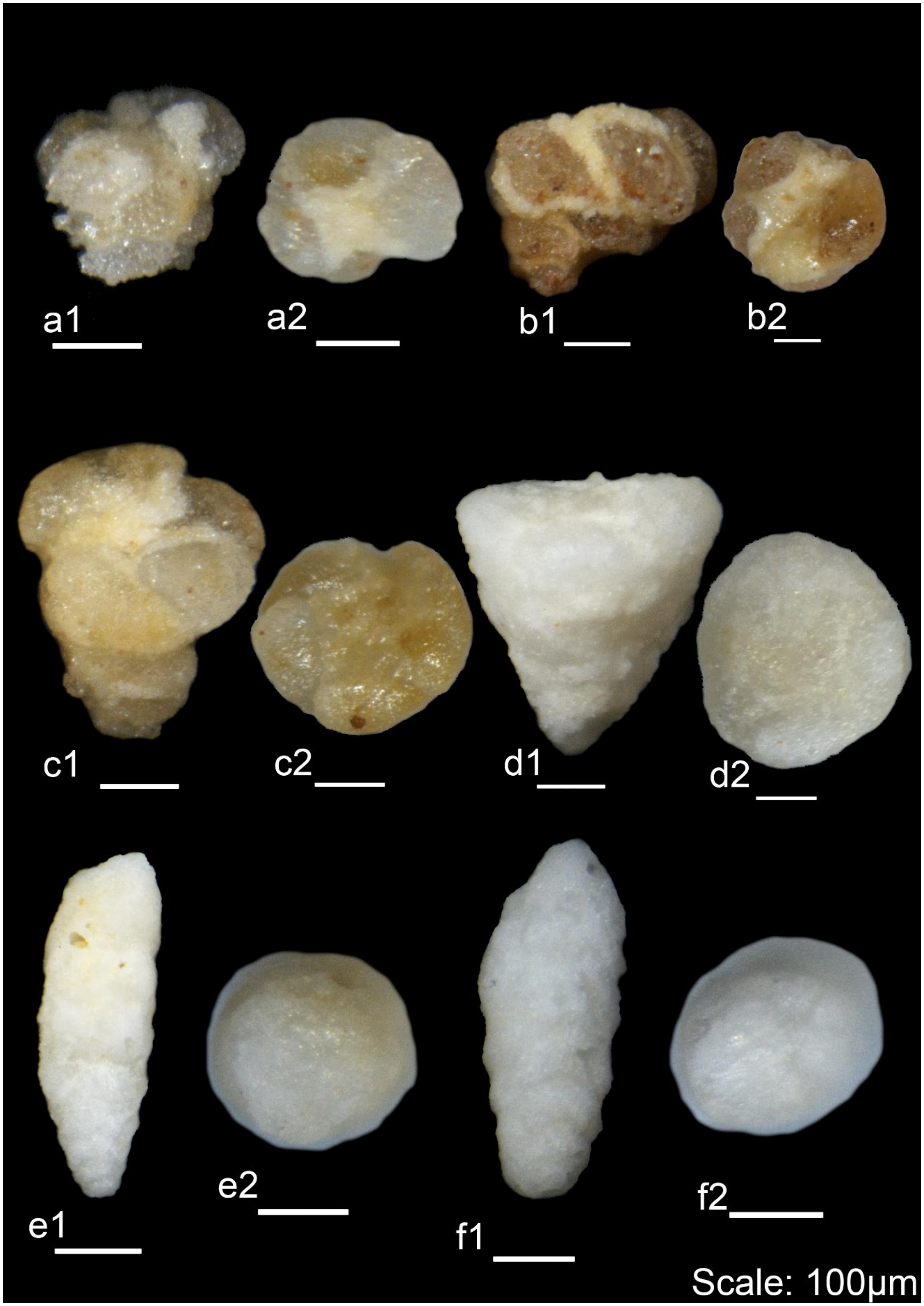


Plate 5.9. A. *Siphovalvulina* sp. 4, Sample 45. **B.** *Siphovalvulina* sp. 5, Sample 45. **C.** *Redmondoides media*, Sample 45. **D.** *Redmondoides inflatus,* Sample 65. **E, F.** *Riyadhella regularis,* Sample 65.

5.3.6 Echinoderm Mudstone / Wackstone Facies (Em-w)

The total number of foraminiferal species identified in the echinoderm rich mudstone to wackstone facies are about 15 belonging to 8 different genera. The recovery from all the samples of Em-w facies is fair. The identified species with their percentage distributions are given in Table 5.6. Representative specimens from the facies are shown in Plates 5.10 & 5.11.

Table 5.6: Foraminifera species and their % distribution in samples of echinoderm mudstone / wackestone facies.

Species / **Sample No.**	***Riyadhella regularis***	***Riyadhella elongata***	***Riyadhella inflata***	***Riyadhella* sp.**	***Riyadhoides mcclurei***	***Redmondoides inflatus***	***Redmondoides media***	***Redmondoides rotundatus***	***Redmondoides primitivus***	***Redmondoides* sp.**	***Siphovalvulina* sp.**	***Lenticulina* sp.**	***Polymorphina* sp.**	***Pseudonodosaria hybrida***	***Nautiloculina* sp.**
04 (%)	6	2	--	16		36	2	--	--	--	13	--	--	--	8
07 (%)	--	2	--	2	--	28	3	8	3	10	--	--	4	0.5	13
36A (%)	2	--	15	3	1	12	--	9	--	--	--	4	6	--	3

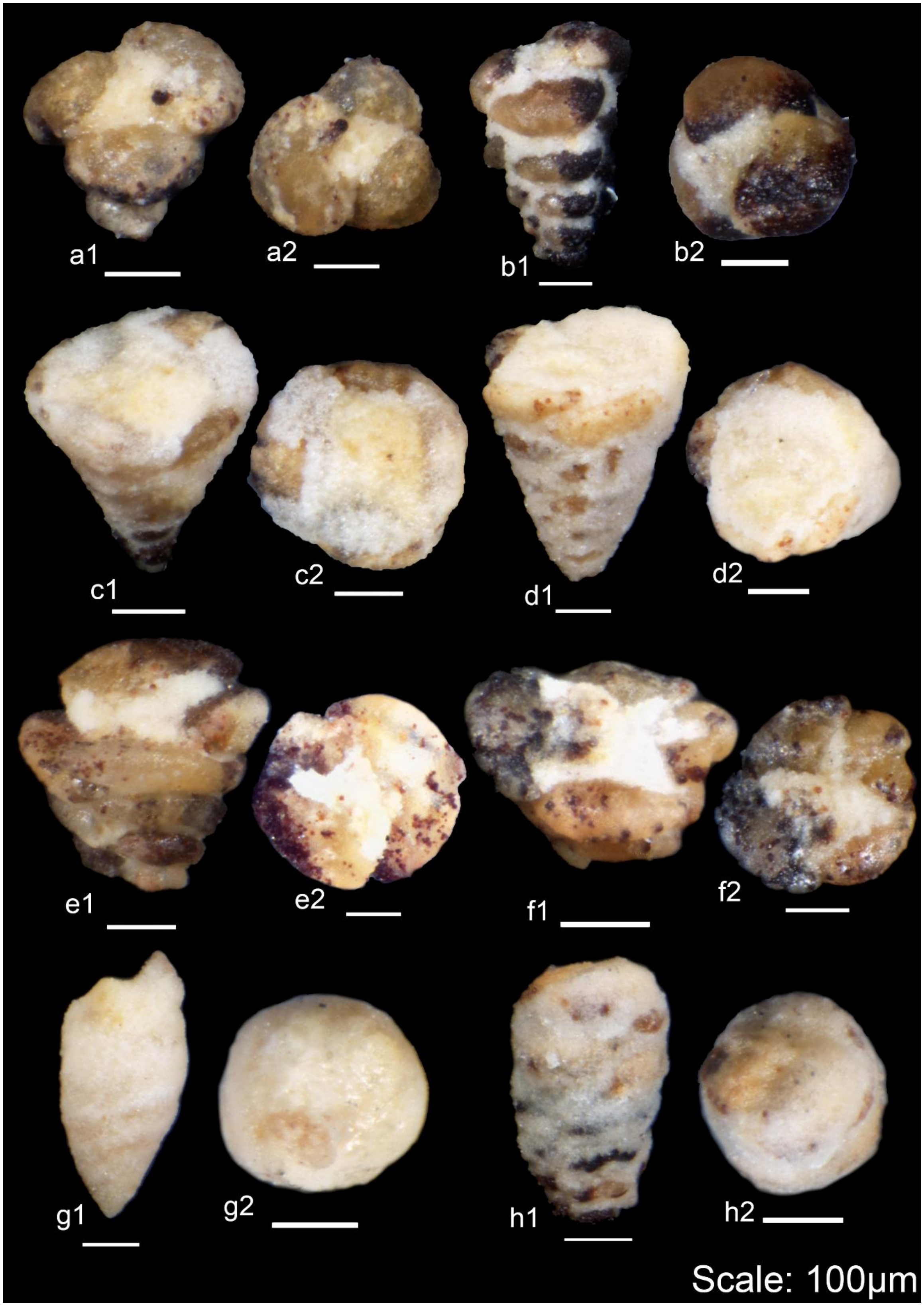


Plate 5.10. A. *Siphovalvulina* sp. 6, Sample 04. **B.** *Siphovalvulina* sp. 7, Sample 04. **C, D, E, F.** *Redmondoides inflatus*, Sample 04. **G.** *Riyadhella* sp. 1, Sample 04. **H.** *Riyadhella* sp. 2, Sample 04.

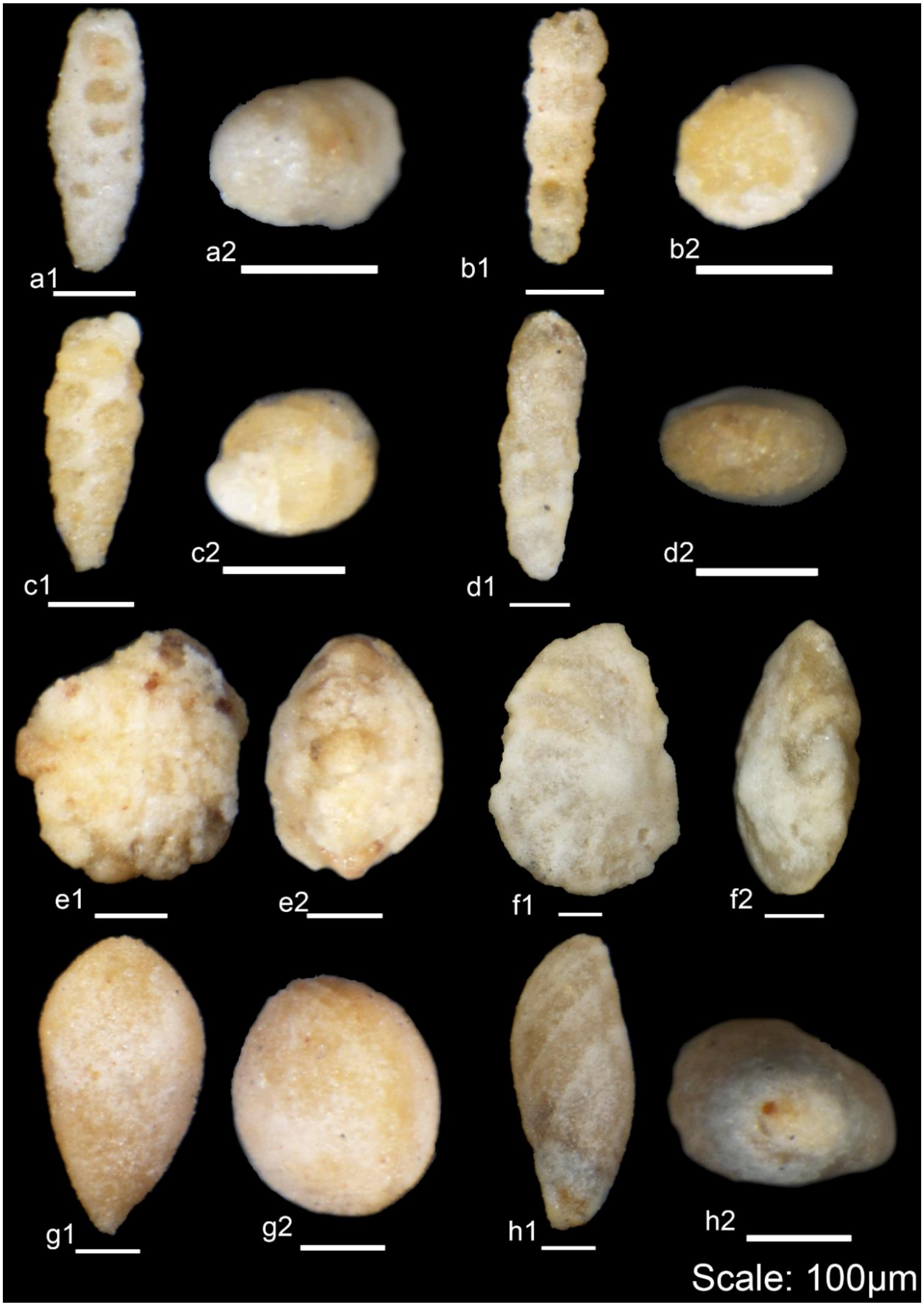


Plate 5.11. A, C. *Riyadhella elongata,* Sample 04, 07. **B.** *Pseudonodosaria hybrid,* Sample 07. **D.** *Lingulina sp.,* Sample 36A. **E.** *Nautiloculina* sp. 2, Sample 04. **F.** *Lenticulina* sp. 4, Sample 07. **G.** *Polymorphina* sp. 3, Sample 07. **H.** *Polymorphina* sp. 4, Sample 36A.

5.3.7 Bioclastic Oolitic grainstone Facies (Bog)

The total number of foraminiferal species identified in the bioclastic oolitic grainstone facies are about 11 which belong to 6 different genera. The samples of Bog species are rich is gastropods and have relatively less foraminifera. The recovery is also fair with nearly 150 specimens per sample. These foraminiferal species along with their distributions in samples are given under in Table 5.7. Representative specimens from the facies are shown in Plates 5.12 & 5.13.

Table 5.7: Foraminifera species and their % distribution in samples of bioclastic oolitic grainstone facies.

Species / **Sample No.**	***Riyadhella regularis***	***Riyadhella inflata***	***Redmondoides inflatus***	***Redmondoides media***	***Redmondoides rotundatus***	***Redmondoides lugeoni***	***Redmondoides* sp.**	***Siphovalvulina* sp.**	***Lenticulina* sp.**	***Polymorphina* sp.**	***Nodosaria* sp.**
30 (%)	--	--	8	4.6	4	2	2	2	11.5	13	3.3
33 (%)	13	6.6	2	3.3	2.6	--	--	6.6	19	6.6	--

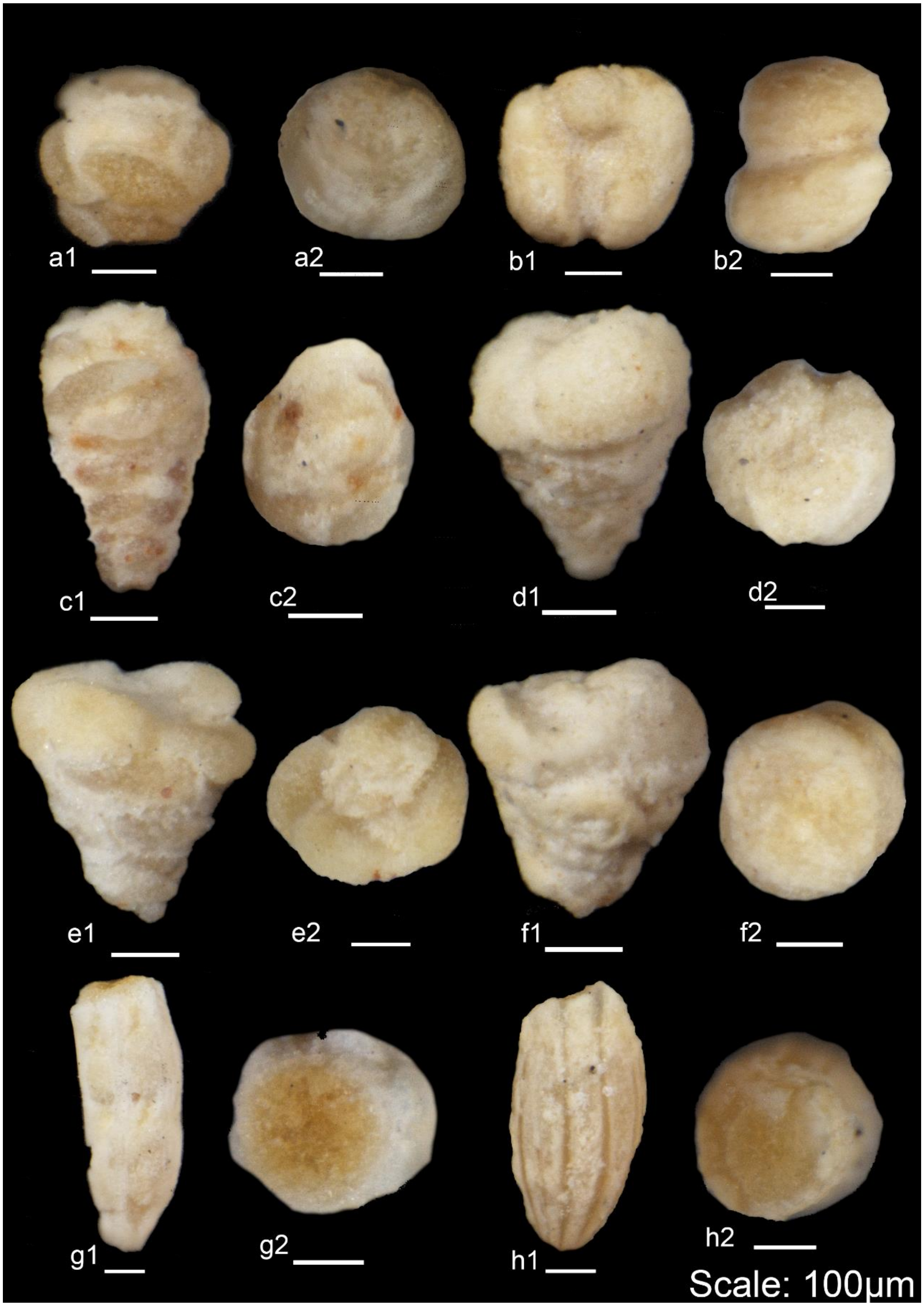


Plate 5.12. A. *Redmondoides lugeoni,* Sample 30. **B.** *Redmondoides* sp. 1, Sample 30. **C.** *Redmondoides media,* Sample 30. **D.** *Redmondoides rotundatus,* Sample 30. **E, F.** *Redmondoides inflatus,* Sample 30. **G.** *Nodosaria* sp. 1, Sample 30. **H.** *Nodosaria* sp. 2, Sample 30.

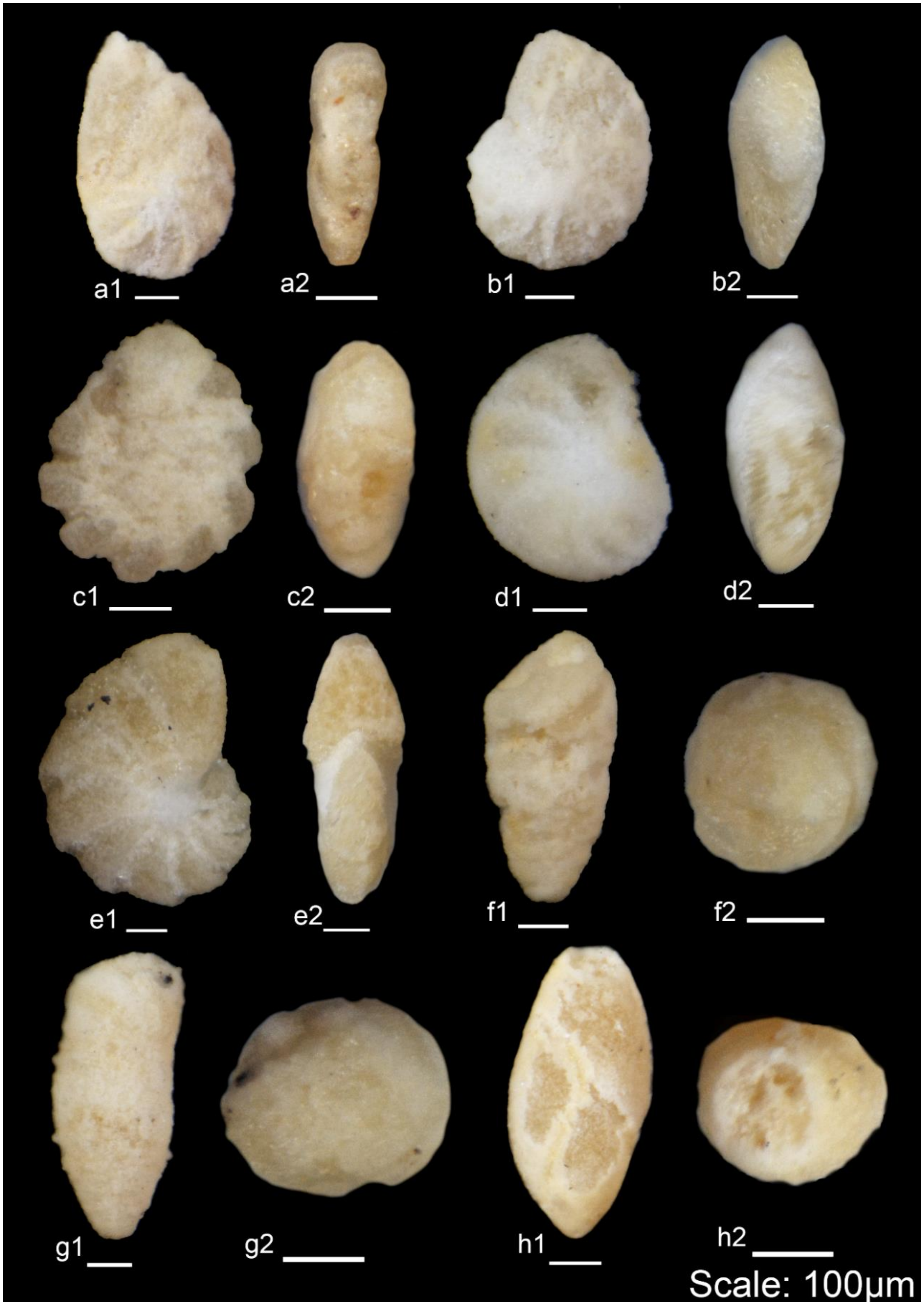


Plate 5.13. A. *Lenticulina* sp. 5, Sample 30. **B.** *Lenticulina* sp. 6, Sample 30. **C.** *Lenticulina* sp. 7, (Sample 30). **D.** *Lenticulina* sp. 8, Sample 33. **E.** *Lenticulina* sp. 9, Sample 33. **F.** *Redmondoides* sp. 2, Sample 33. **G.** *Redmondoides* sp. 3, Sample 30.

5.3.8 Foraminiferal Wackestone Facies (Fw)

The total number of foraminiferal species identified in the foraminiferal wackestone facies are about 13 which belong to 8 different genera. The species is very rich in foraminifera with almost no gastropods and ostracods. The identified foraminifera with their percentage abundance in samples are given as under in Table 5.8. Representative specimens from the facies are shown in Plates 5.14 & 5.15.

Table 5.8: Foraminifera species and their % distribution in samples of foraminiferal wackestone facies.

Species / **Sample No.**	***Riyadhella regularis***	***Rashnovammina carpathica***	***Redmondoides inflatus***	***Redmondoides media***	***Redmondoides rotundatus***	***Andersenolina alpina***	***Andersenolina elongata***	***Pfenderina gracilis***	***Pfenderina inflata***	***Kurnubia bramkampi***	***Kurnubia variabilis***	***Lenticulina* sp.**	***Nautiloculina* sp.**
62 (%)	1.6	0.3	4	5.6	5	10	9	8.3	21	4	3.6	--	8
68 (%)	--	1.2	6	18	10	--	--	5	5.5	6.6	2	27	5

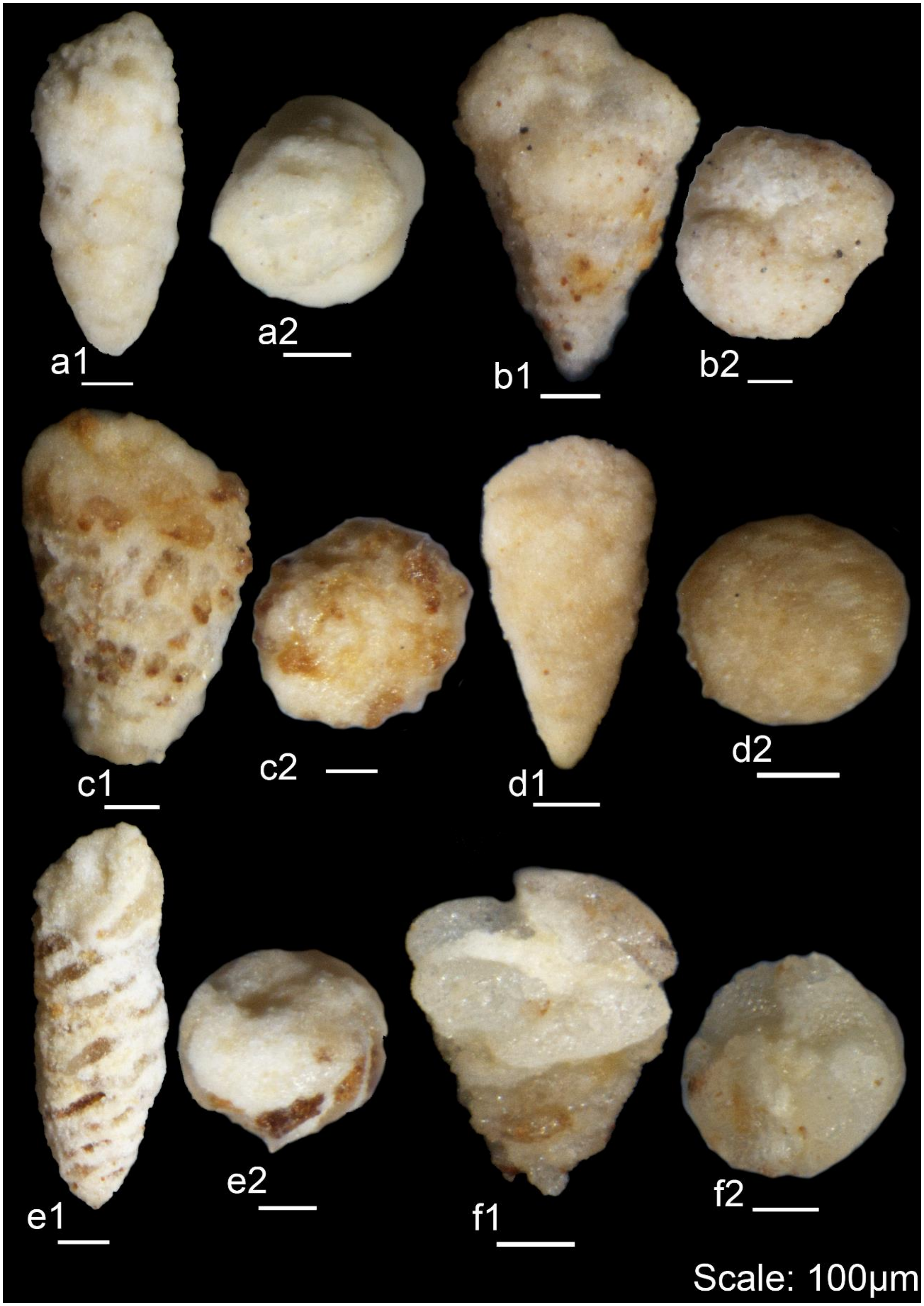


Plate 5.14. A. *Riyadhella regularis,* Sample 62. **B.** *Redmondoides rotundatus,* Sample 62. **C.** *Kurnubia variabilis*, Sample 62. **D.** *Kurnubia bramkampi*, Sample 62. **E.** Pfenderina inflata, Sample 62. **F.** *Redmondoides inflatus,* Sample 62.

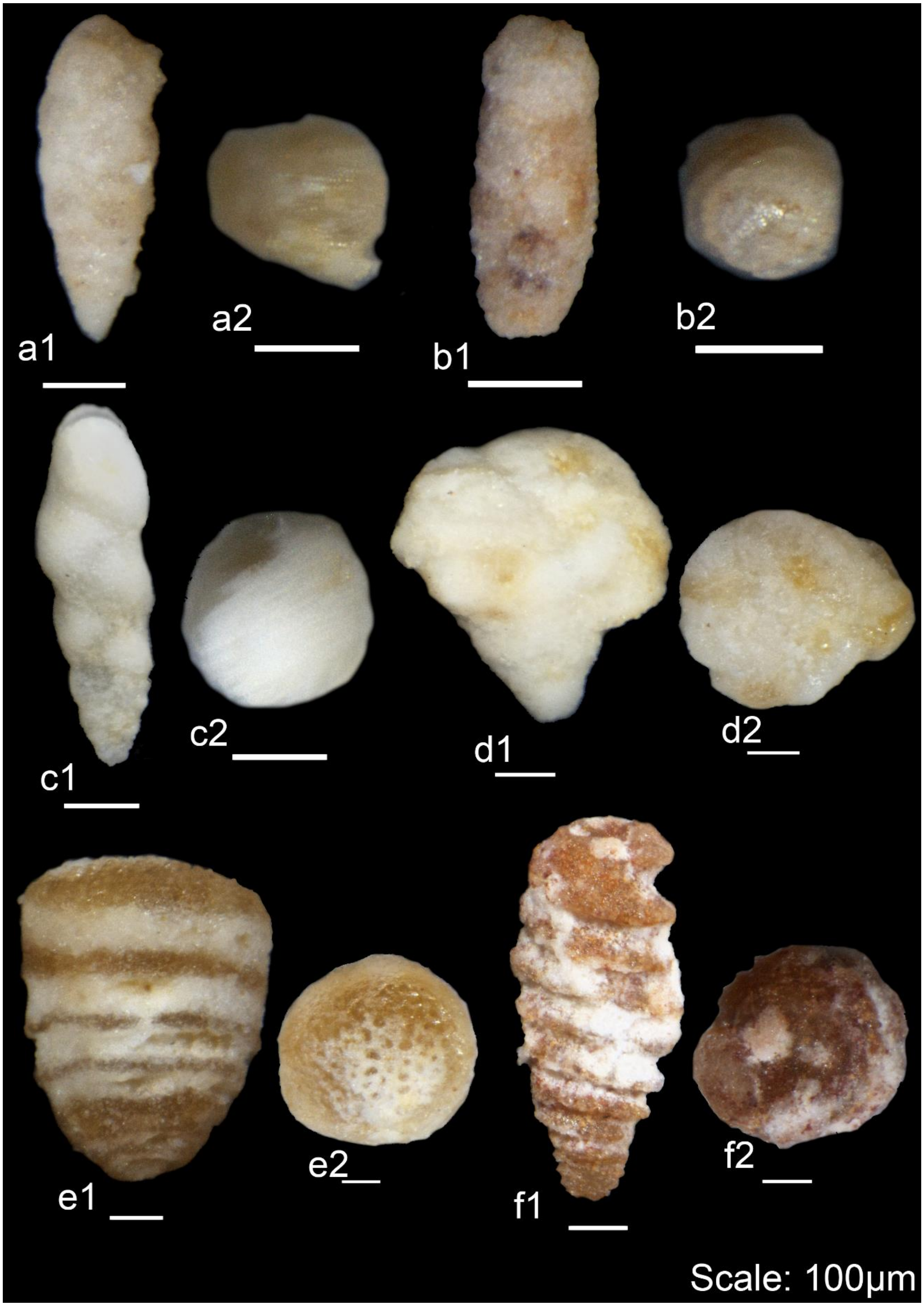


Plate 5.15. A, B. *Riyadhella regularis,* Sample 62. **C.** *Rashnovammina carpathica,* Sample 68. **D.** *Redmondoides media,* Sample 62. **E.** *Andersenolina alpina,* Sample 62. **F.** *Andersenolina elongate,* Sample 62.

5.3.9 Spiculitic pelloidal grain dominated Packstone Facies (Spgdp)

The total number of foraminiferal species identified in the spiculitic pelloidal grain dominated packstone facies are about 12 belonging to 11 different genera. The fossil recovery from samples is fair. The identified foraminifera species along with their percentage distributions are given in Table 5.9. Representative specimens from the facies are shown in Plate 5.16.

Table 5.9: Foraminifera species and their % distribution in samples of spiculitic pelloidal grain dominated packstone facies.

Species / Sample No.	*Riyadhella regularis*	*Riyadhoides mcclurei*	*Redmondoides inflatus*	*Redmondoides media*	*Siphovalvulina* sp.	*Spirillina* sp.	*Lenticulina* sp.	*Pseudomarssonella* sp.	*Everticyclammina contorta*	*Polymorphina* sp.	*Pseudonodosaria* sp.	*Posadia* sp.
11A (%)	2	--	16	47	10	0.6	6	2	--	2	--	--
15 (%)	2	--	17	13	17	6	9	3.3	0.6	4	--	0.6
42 (%)	37	5	7	15	3.3	--	3.3	1.1	--	--	3	2.2

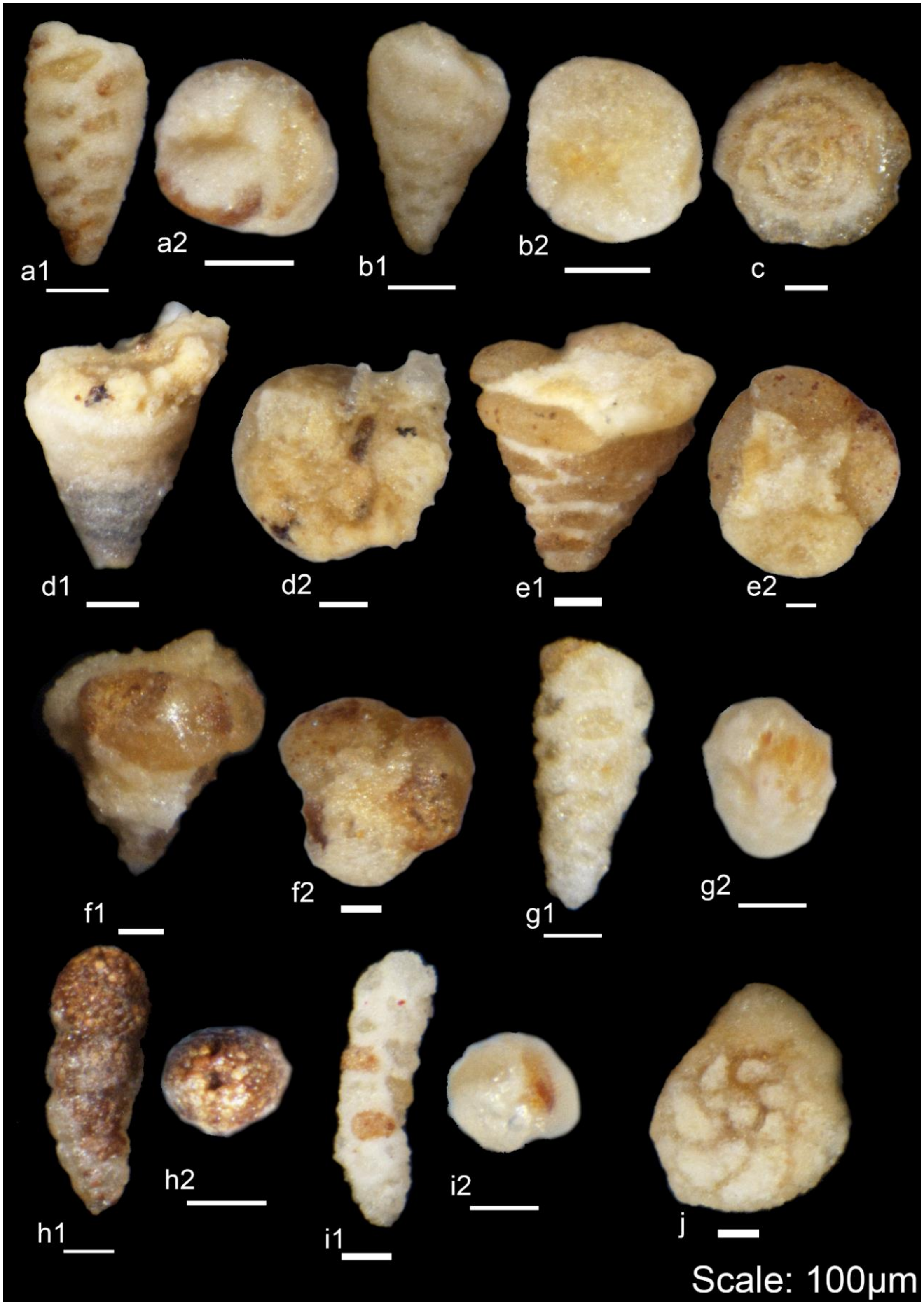


Plate 5.16. A, B. *Redmondoides media*, Sample 11A. **C.** *Spirillina* sp. 2, Sample 11A. **D.** *Pseudomarssonella* sp. 1, Sample 11A. **E.** *Redmondoides inflatus*, Sample 11A. **F.** *Siphovalvulina* sp. 8, Sample 11A. **G.** *Riyadhella regularis*, Sample 42. **H.** *Posadia* sp. 1, Sample 11A. **I.** *Riyadhoides mcclurei*, Sample 42. **J.** *Everticyclammina contorta*, Sample 11A.

5.3.10 Skeletal Mudstone Facies (Ms)

The total number of foraminiferal species identified in the mudstone facies are about 13 belonging to 9 different genera. The foraminifera recovered from muds are clean as no acid was used in the process. Most of the samples show fair to good recovery but some are found to be empty also. The identified foraminifera species with their percentage distributions in samples are given in Table 5.10. Representative specimens from the facies are shown in Plates 5.17, 5.18 & 5.19.

Table 5.10: Foraminifera species and their % distribution in samples of skeletal mudstone facies.

Species / **Sample No.**	***Riyadhella regularis***	***Riyadhella inflata***	***Redmondoides inflatus***	***Redmondoides media***	***Redmondoides rotundatus***	***Pfenderina gracilis***	***Pfenderina inflata***	***Lingulina* sp.**	***Lenticulina* sp.**	***Polymorphina* sp.**	***Pseudonodosaria* sp.**	***Nodosaria* sp.**	***Nautiloculina* sp.**
03A(%)	1.7	--	24	19	23	--	--	--	12	--	--	--	--
06A(%)	18	--	10	23	13	--	--	--	15	--	5	13	--
09A(%)	4	--	12	20	4	--	--	--	17	--	2	--	--
18B(%)	1.3	--	27	10	16	--	--	--	28	0.6	3.6	1.3	--
40 (%)	1.1	51	7.5	5	6	--	--	--	--	1.1	--	--	6
57 (%)	2.7	5	25	7.2	12	2	2	1	20	1	--	2.7	--
64 (%)	20	--	11	4	7.2	22	11	0.8	16	--	0.8	--	--
67 (%)	4	--	5.3	4.6	9.2	11	3.3	0.6	21	--	2	--	2

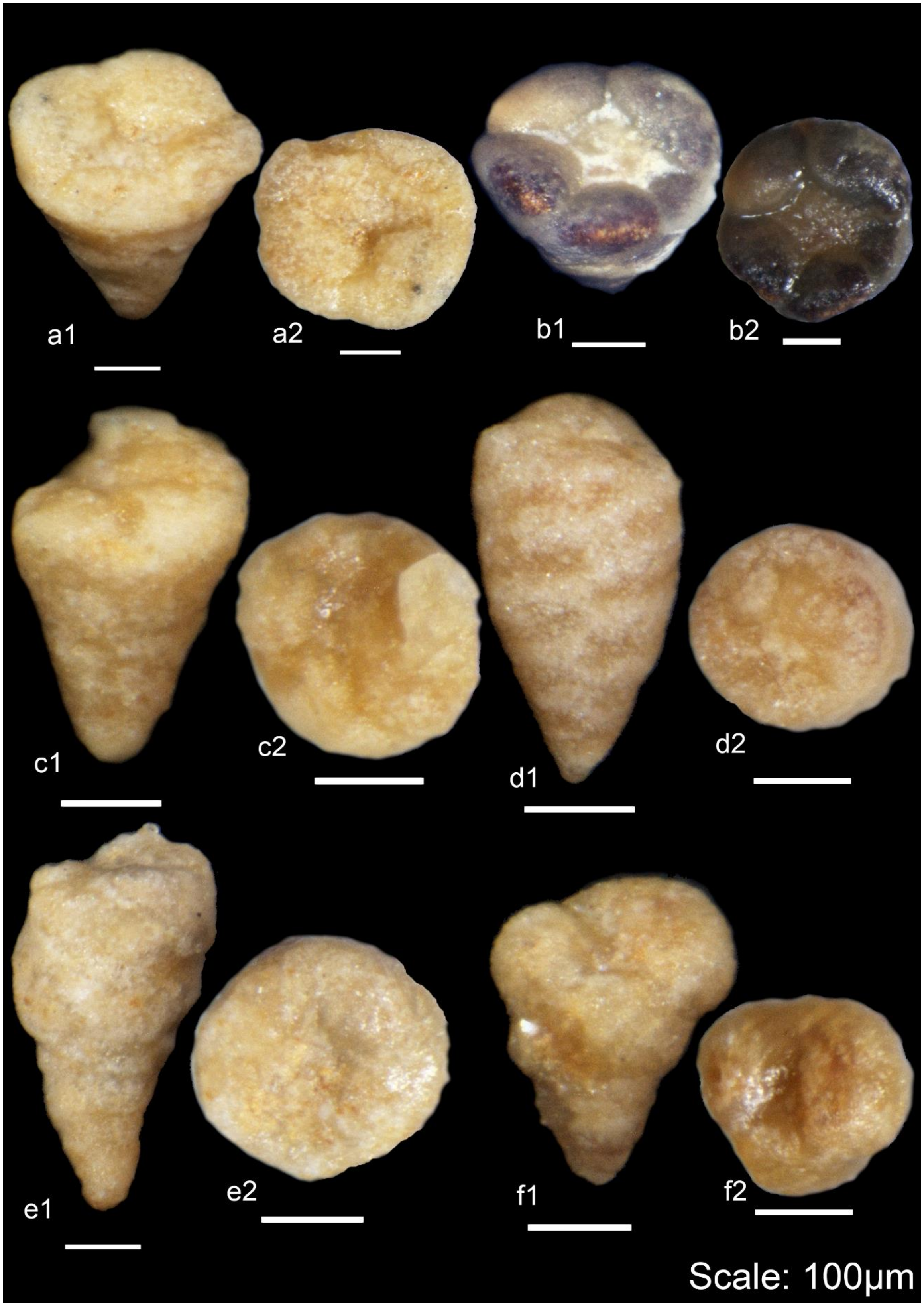


Plate 5.17. A, B. *Redmondoides inflatus,* Sample 03A. **C, D.** *Redmondoides media,* Sample 03A. **E.** *Redmondoides primitivus,* Sample 03A. **F.** *Redmondoides rotundatus,* Sample 03A.

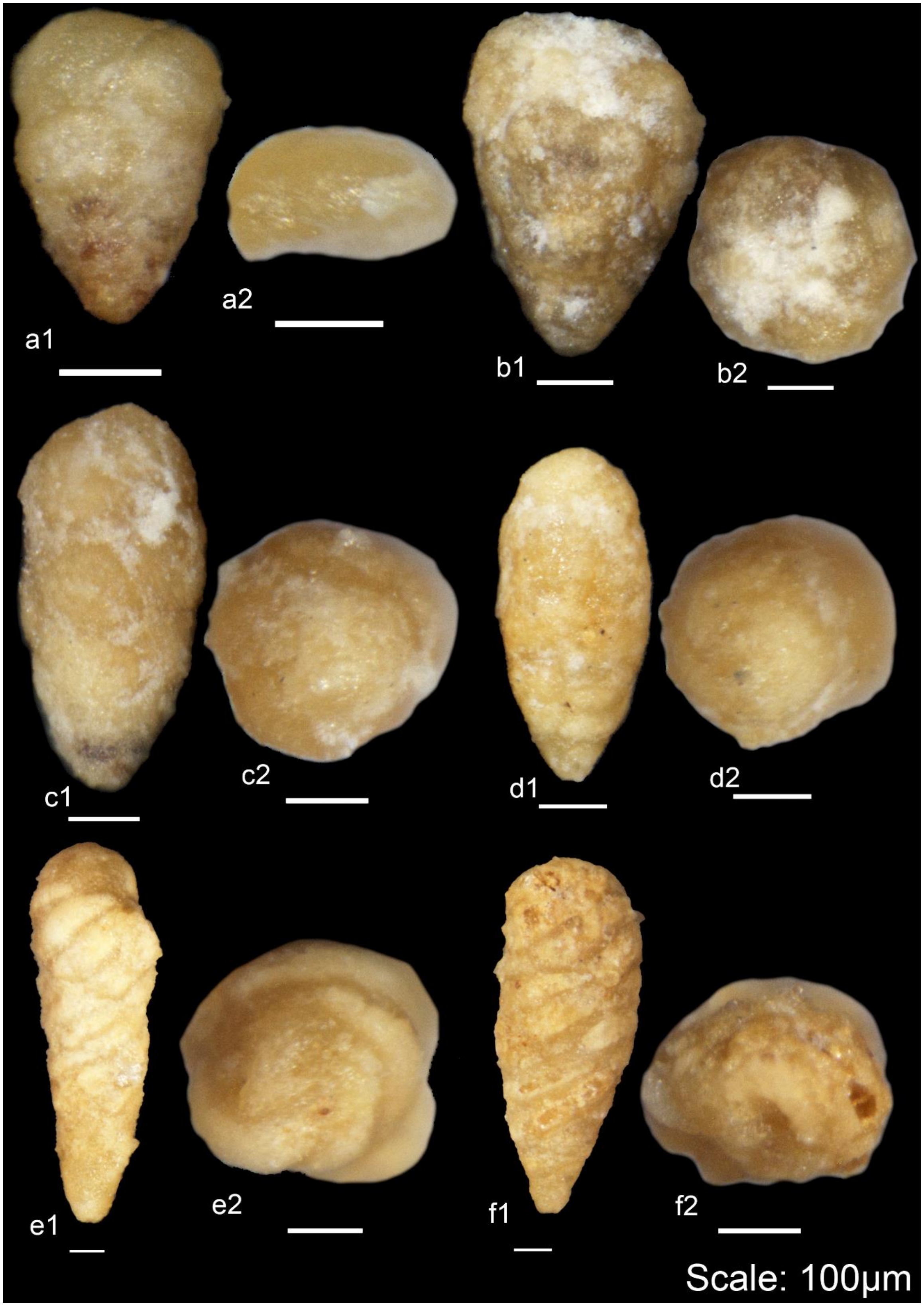


Plate 5.18. A. *Redmondoides rotundatus,* Sample 40. **B.** *Riyadhella inflata,* Sample 40. **C, D.** *Riyadhella regularis,* Sample 40. **E.** *Pfenderina gracilis,* Sample 64. **F.** *Pfenderina inflata,* Sample 64.

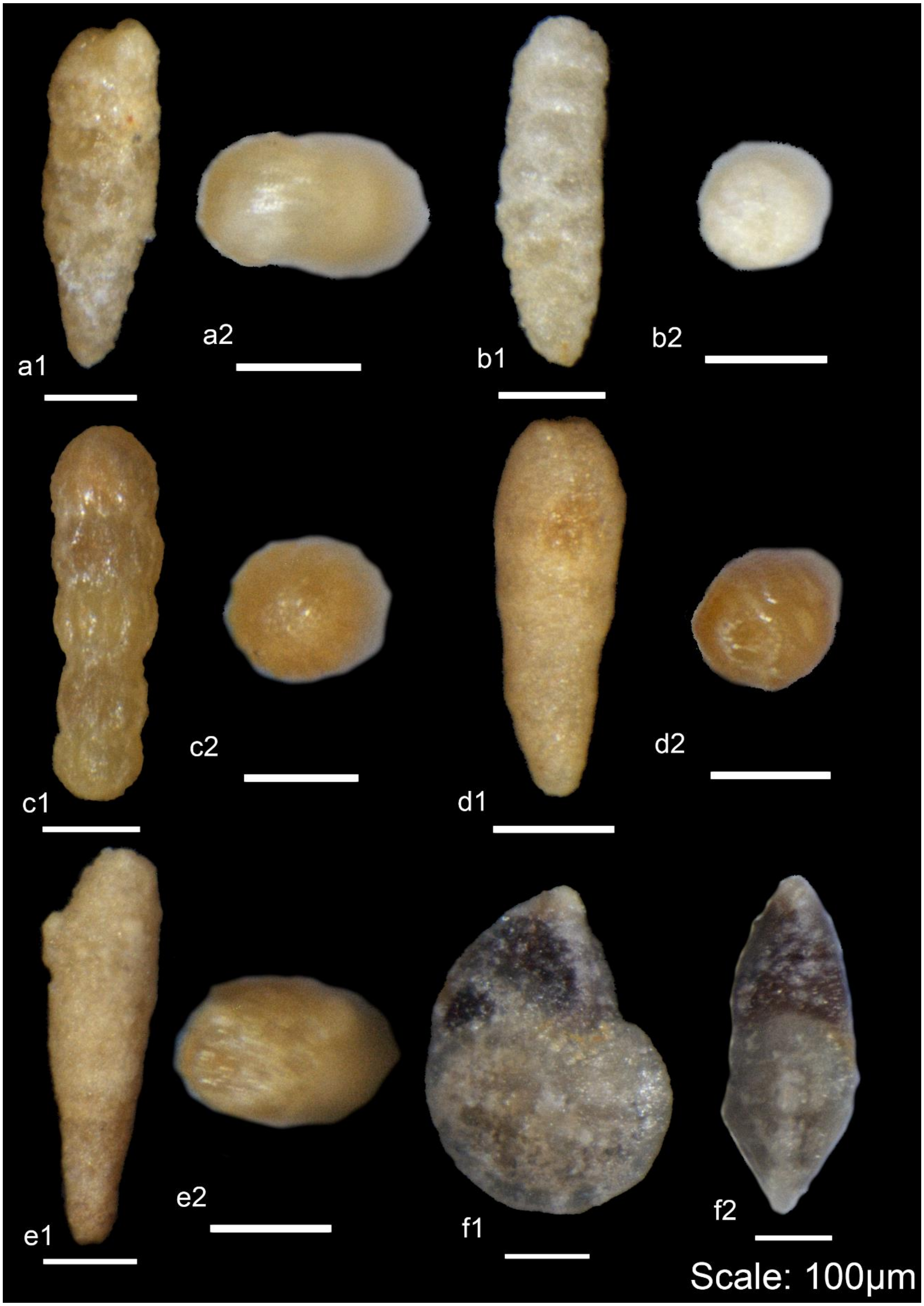


Plate 5.19. A, B. *Riyadhoides mcclurei,* Sample 64. **C.** *Nodosaria fontinensis,* Sample 18B. **D, E.** *Pseudonodosaria vulgata,* Sample 18B. **F.** *Lenticulina* sp., Sample 03A.

CHAPTER 6

DISCUSSIONS & CONCLUSIONS

6.1 Discussion

The results of the lithostratigraphic and biostratigraphic study identified 10 lithofacies, their skeletal and non-skeletal components, geochemical analysis (XRF, XRD), SEM images, as well as the microfossil species and genera. The available data once integrated and the results obtained help us in developing a detailed stratigraphy, sedimentology and micropaleontology of the D5 member of Middle Jurassic Dhruma Formation. The stratigraphic log along with the distribution of lithofacies and their details as per the samples studied in the outcrop along with thin sections data is shown in Figure 6.1. These details along with the extracted microfossils are used to document and interpret the depositional environment of the formation, its sequence stratigraphic framework, as well as the identification of foraminiferal ranges. The detailed interpretation of the outcrop is given under separate points of depositional environment, sequence stratigraphy, and biostratigraphy

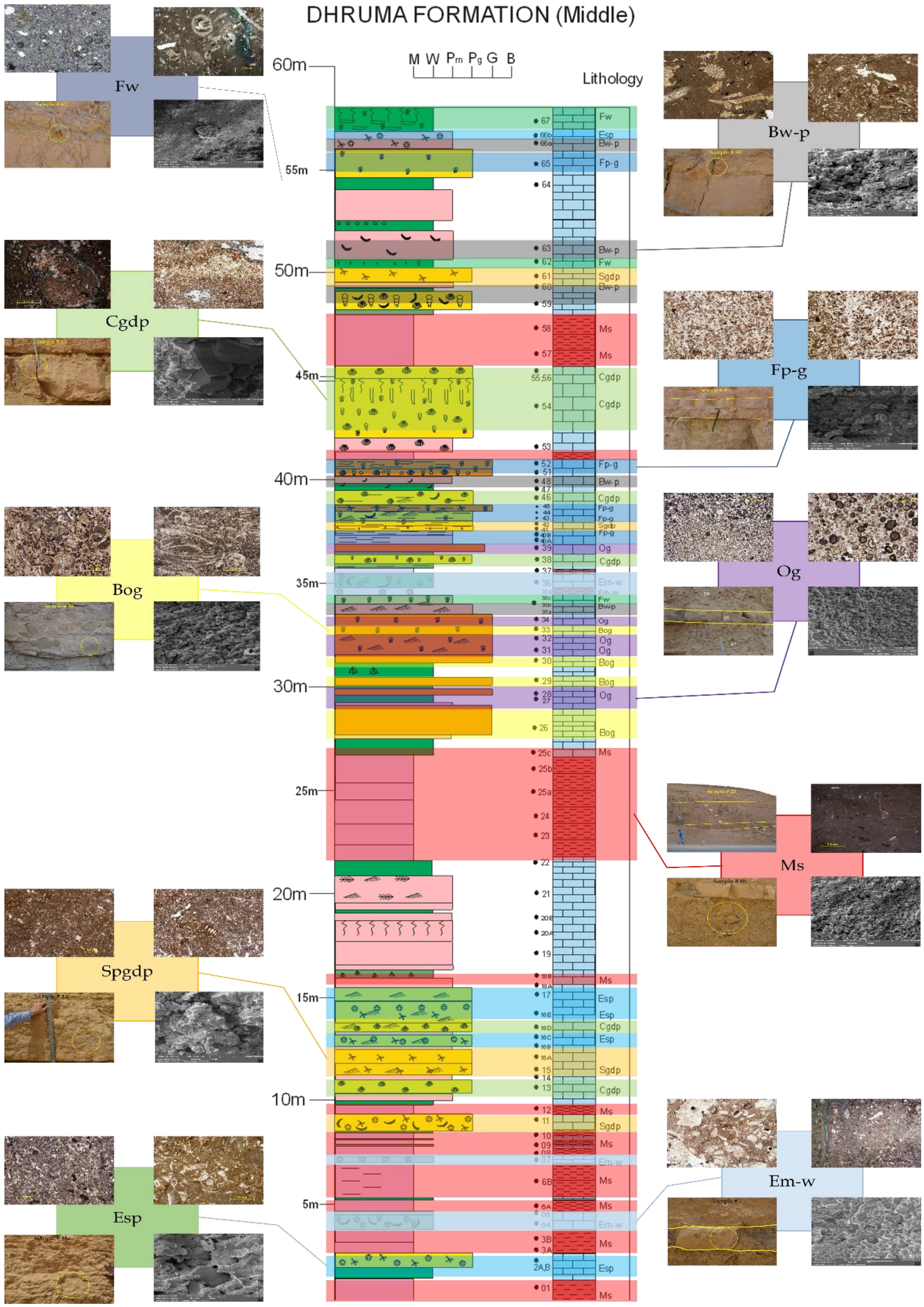


Figure 6.1: Stratigraphic log with the identified facies, their distribution and details

6.1.1 Depositional environment

For interpreting the depositional environment of the outcrop, several parameters are used including the sedimentary features present on the surface of the outcrop, the skeletal and non-skeletal components and the habitat of certain representative fauna present in the lithofacies. A generalized table giving the use of surface sedimentary features seen on the outcrop for interpreting the depositional environment is given below in Figure 6.2.

No of Facies	Facies Name	Features	Environment of Deposition
1	Echinoderm spiculitic Packstone facies (Esp)	Burrowed, Small scale X-bedding & horizontal lamination	**Inner to mid ramp (Medium energy)**
2	Oolitic grainstone facies (Og)	Small scale X-bedding and herring bone	**Inner Ramp (High energy)**
3	Bioclastic wackestone/Packstone facies (Bw-p)	Burrowed	**Mid ramp**
4	Foraminiferal packstone/grainstone facies (Fp-g)	Small scale X-bedding & horizontal lamination	**Ramp Crest facies, Ramp & shelf margins**
5	Coral bearing grain dominated packstone facies (Cgdp)	Small scale X-bedding & horizontal lamination	**Inner to Mid Ramp (High energy)**
6	Echinoderm mudstone/ wackstone facies (Em-w)	Few Borrows	**Mid to outer ramp (Low Energy)**
7	Bioclastic oolitic grainstone facies (Bog)	Small scale X-bedding and herring bone	**Inner Ramp (High energy)**
8	Foraminiferal wackestone facies (Fw)	Burrows	**Mid to outer ramp (Low energy)**
9	Spiculitic Pelloidal grain dominated Packstone facies (Spgdp)	Small scale X-bedding & horizontal lamination Channelized with pebbles and quartz fragments	**Inner Ramp (High energy)**
10	Skeletal Mudstone facies (Ms)	Nodular muds	**Outer Ramps (Low energy)**

Figure 6.2: Lithofacies with their sedimentary features and interpreted environment of deposition.

Along with the above surface features, the use of other skeletal and non-skeletal components present in the samples also identify the environment as shallow open marine. Corals are representative of warm, shallow, well-oxygenated calm waters of tropical to sub-tropical regions and are also sensitive to salinity. Echinoderms also show a similar trend and are mostly representative of open marine facies due to their sensitivity to saline waters. Sponges are also present in clear waters and calcareous sponges are representative of shallow waters. The benthic foraminifera are also present in shallow tropical open marine waters and are sensitive to water currents and depth.

The non-skeletal grains present include the intraclasts which are of shallow marine origin. Pelloids are representative of shallow marine non-agitated waters. Ooids belong to warm open waters agitated with tidal currents. The waters bearing ooids are very shallow approximately 2–7 m deep but ooids can also be carried away by storms to deeper environments.

Paleogeographically, during the Jurassic times the Arabian Peninsula was located at the southern margin of the Tethys ocean and was a site of an extensive shallow marine platform (Al-Hussaini, 1997). This also helps our interpretation and by keeping all of the above information in mind the environment of deposition is considered to be subtidal with facies deposited on the middle portion of a shallow open marine ramp. The same subtidal environment was interpreted by Fischer et al. (2001) based on ammonites from the D5 & D6 members of the Dhruma Formation. Enay (1987) also assigned a subtidal environment to the Dhruma Formation. The deposition model for the outcrop is given in Figure 6.3.

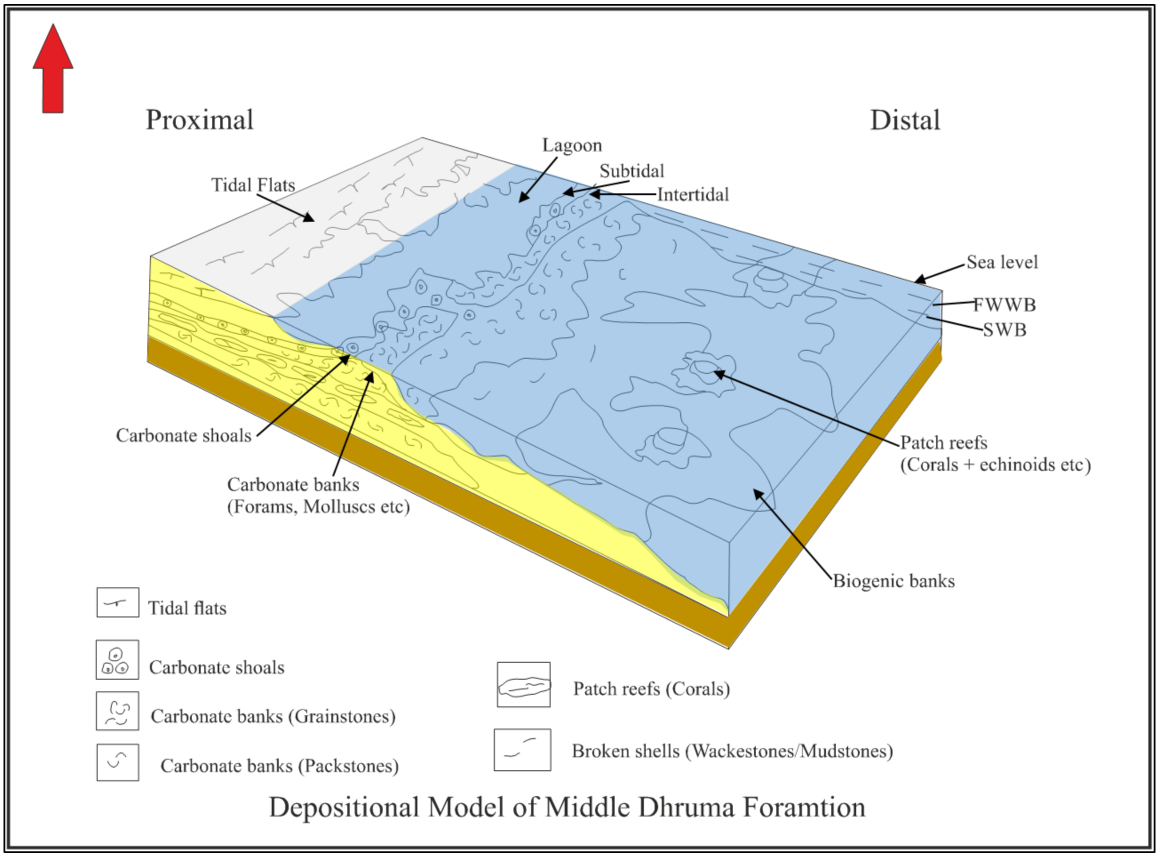


Figure 6.3: Depositional model of the D5 member of the Middle Jurassic Dhruma Formation.

6.1.2 Sequence Stratigraphy

For sequence stratigraphic interpretation, sequences are interpreted based on the high frequency cycles of 5^{th} to 6^{th} order resolution. These high frequency cycles are made either from coarsening upward or fining upward successions of the facies. From our outcrop, 18 cycles have been interpreted, out of which 12 show fining upward and 6 show coarsening upward successions. These cycles are then combined into 6 high frequency sequences which further correspond to the 3 composite sequences. 2 sequence boundaries (SB) are also identified between the high stand system tracts (HST) and the transgressive system tracts (TST).

In the lower portion of the outcrop, a thick unit of mud is present. When marked by the sequences, the unit comes between the transgressive system track and the high stand system tract. Sharland et al. (2001) & Enay et al. (2009) identified a maximum flooding surface (MFS) in the lower portion of D5 member. Enay et al. (2009) identified of maximum flooding surfaces based on the ammonite data, and Sharland et al. (2001) only described one foraminiferal species (*Riyadhella arabica)* from the maximum flooding surface. The thick muddy unit encountered in the lower portion of the outcrop might be considered as a candidate for the maximum flooding surface or zone unit (indicated by dotted line) but limitations are present. These limitations include non-availability of the ammonite data for the study and also the bad recovery of microfossils especially foraminifera from the unit, which might be the result of weathering because unit is highly friable and weathered and fresh samples are very difficult to obtain. The sequence stratigraphic framework of the outcrop is given in Figure 6.4.

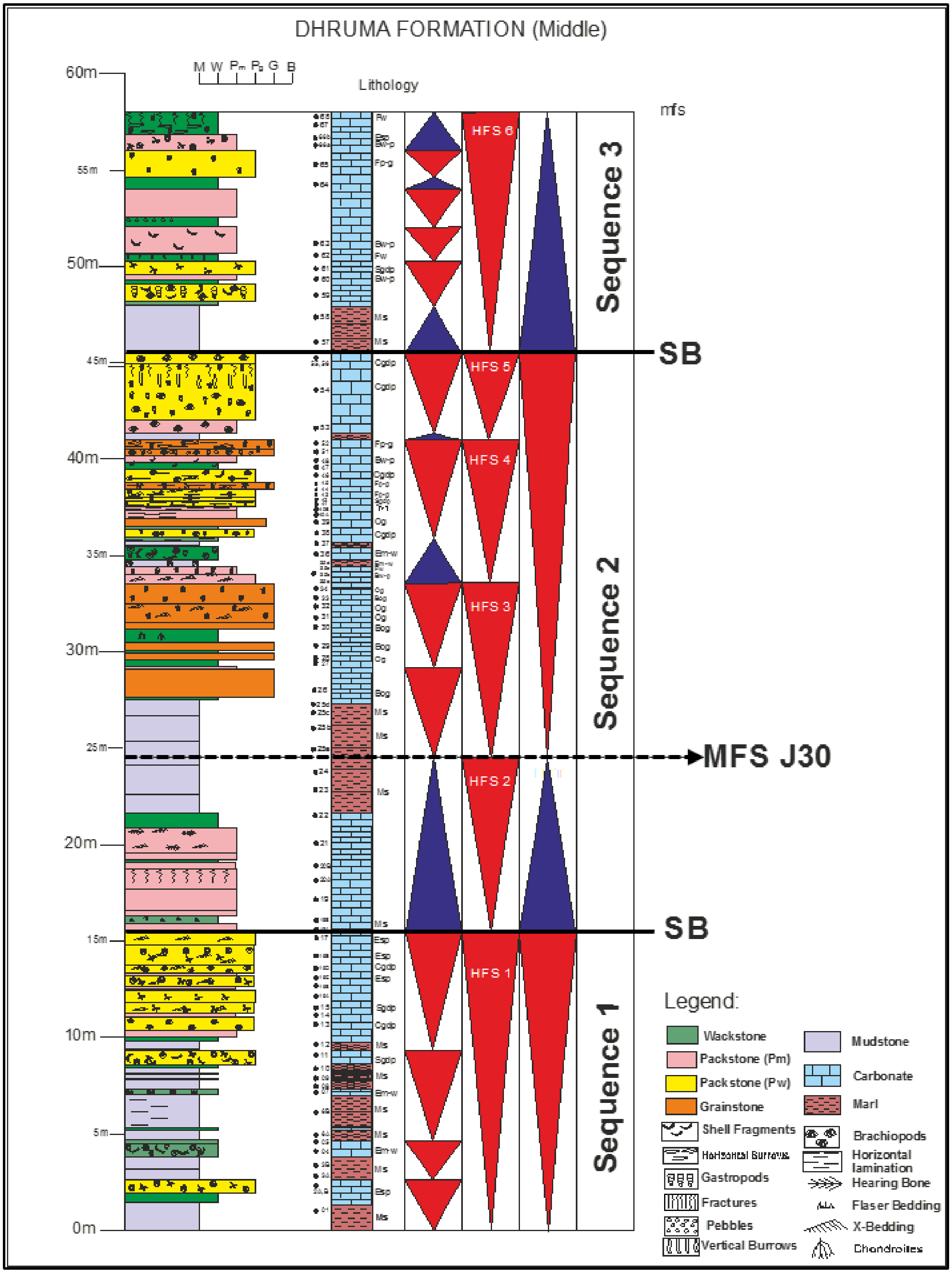


Figure 6.4: Sequence stratigraphic framework of the D5 member of Middle Jurassic Dhruma Formation.

6.1.3. Foraminifera Biozones

As discussed in the micropaleontology chapter, from our outcrop we identified 35 foraminifera species and 19 genera. When these species are plotted against the stratigraphic column, we can see the distribution of species throughout the outcrop. This also enables us to determine the ranges of foraminifera species by their first and last occurrences. For our outcrop, we identified 11 foraminiferal biozones. These biozones are important because certain species of foraminifera occur only in certain depositional environment so are restricted to certain lithofacies. Once identified these act as useful markers in petroleum exploration specially in fields of directional drilling and bio-steering which are based on these ranges for certain specific intervals of the reservoirs. The identified biozones are given below in Figure 6.5 while the ranges of foraminifera species are given in Figure 6.6.

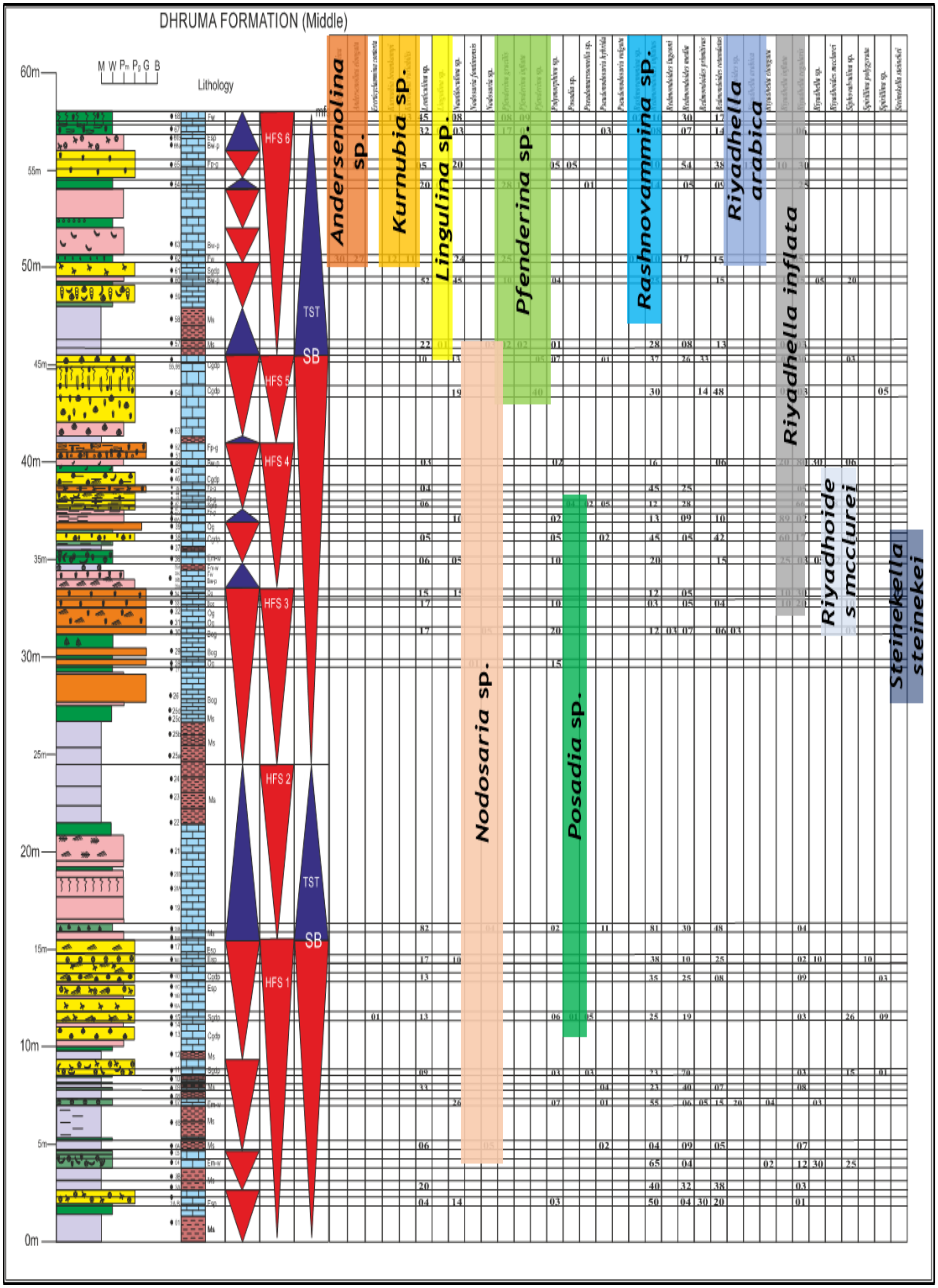


Figure 6.5: Foraminifera biozones identified in the outcrop. Colored columns show the range extant based on first and last occurrences of the species.

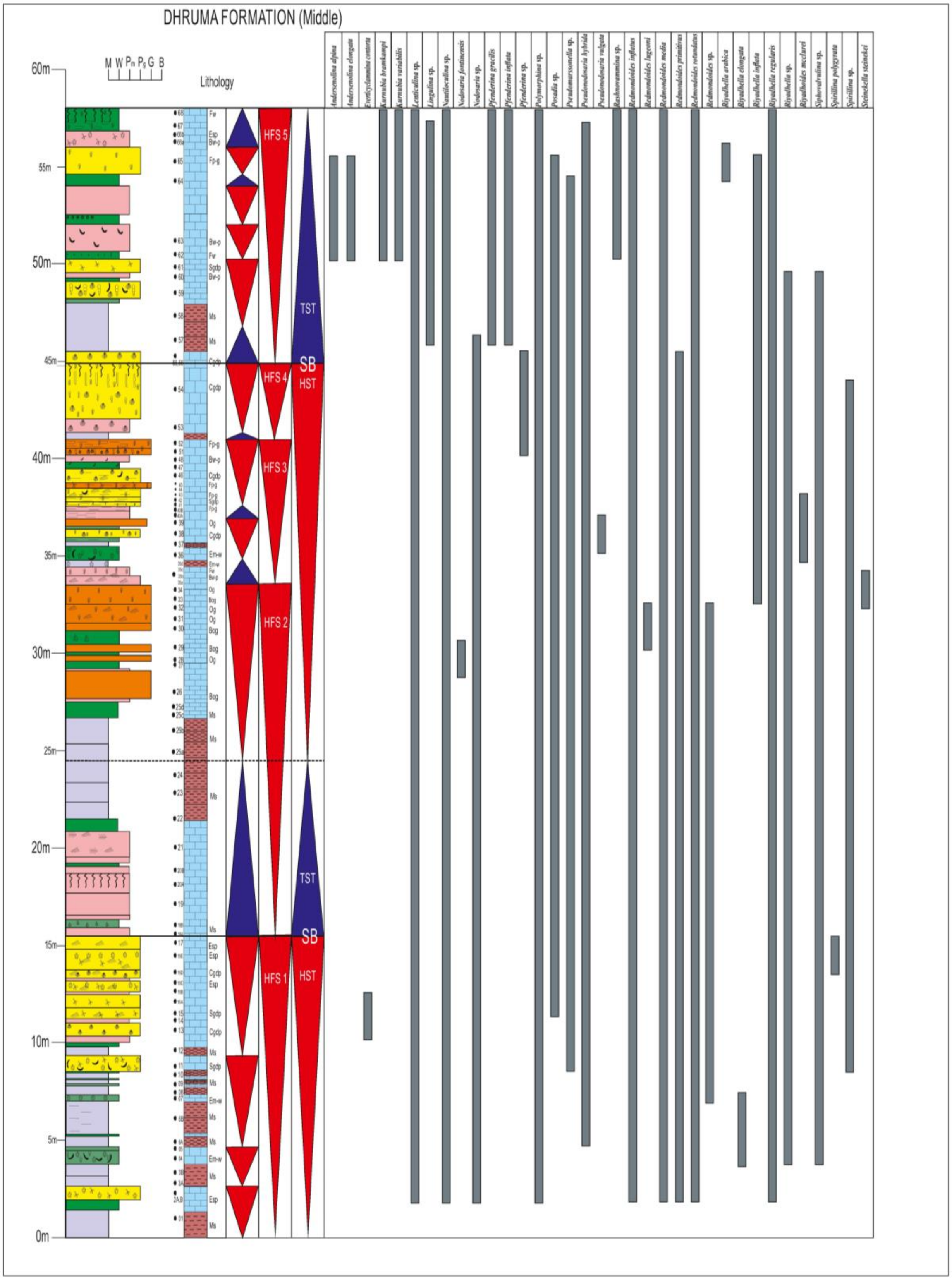


Figure 6.6: Foraminifera ranges identified in the outcrop.

6.2 Conclusions & Recommendations

On the basis of the identified microfacies, sequences and foraminifera ranges, I conclude that the outcrop is representative of the D5 member (Bathonian) of the Dhruma Formation. The studied outcrop can be subdivided into 10 lithofacies ranging from deep marine calm water mudstones to shallow marine high energy oolitic grainstones. By studying the lithofacies along with their skeletal and non-skeletal component the environment of depositional of D5 member is considered to be subtidal with facies deposited on middle part of a shallow open marine ramp. Eleven foraminifera ranges have been identified in the outcrop based on the occurrences of 35 species of foraminifera. From the sequence stratigraphic point of view, the outcrop can be subdivided into 3 fourth order sequences with two sequence boundaries.

Further work is needed for the extension of the study to lower unstudied members of the formation. Reservoir characterization studies can be carried out for the outcrop which will help to determine any possible reservoir potential in the subsurface. Water depth calibrations for the studied microfossils can also help in determination of exact water depths for facies and can be tied with the sequences. The identified ranges or Biozones can be further refined and used in field of petroleum exploration for bio-steering and directional drilling.

APPENDIX

SYSTEMATIC TAXONOMY

SUBORDER HORMOSININA Mikhalevich, 1980

Superfamily HORMOSINOIDEA Haeckel, 1894

Family Hormosinidae Haeckel, 1894

Subfamily Cuneatinae Lobelich & Tappan, 1984

Genus *Posadia* Guisberti & Coccioni, 2003

Type species: *Posadia feronensis* Giusberti & Coccioni, 2003

Posadia sp.

(pl. 5.16, fig. h)

Remarks: Very rare and not well preserved. Only one specimen recovered.

SUBORDER NEZZAZATINA Kaminski, 2004

Superfamily NEZZAZATACEA Hamaoui & Saint-Marc, 1970

Family Nautiloculinidae Loeblich & Tappan, 1985

Genus *Nautiloculina* Mohler, 1938

Type species: *Nautiloculina oolithica* Mohler, 1938; OD.

Nautiloculina sp.

(pl. 5.5, figs. c; pl. 5.11, fig. e)

Nautiloculina sp. MOHLER, 1938, p. 19, pl. 4, figs. 1-3.

SUBORDER LOFTUSIINA Kaminski & Mikhalevich, 2004

Superfamily LOFTUSIACEA Brady, 1884

Family Everticyclamminidae Septfontaine, 1988

Genus *Everticyclammina* Redmond, 1964

Type species: *Everticyclammina hensoni* Redmond, 1964.

Everticyclammina contorta Redmond, 1964

(pl. 5.16, fig. j)

Everticyclammina contorta REDMOND, 1964. p. 408, pl. 1, figs. 12-15.

Everticyclammina contorta Redmond, 1964. -- BANNER & WHITTAKER, 1991, p. 48, pl. 3, figs 5–7; pl. 4, figs 1–3.

SUBORDER SPIROPLECTAMMININA Mikhalevich, 1992

Superfamily SPIROPLECTAMMINOIDEA Cushman, 1927

Family Textulariopsidae Lobelich & Tappan, 1982

Genus *Rashnovammina* Neagu & Neagu, 1995

Type species: *Rashnovammina carpathica* Neagu & Neagu, 1995

Rashnovammina carpathica Neagu & Neagu, 1995

(pl. 5.15, figs. c)

Rashnovammina carpathica Neagu & Neagu, 1995, p. 216, pl. 2, figs 12-27.

Remarks: Our specimen shows loosely biserial chamber arrangement in the last four chambers. These chambers are much higher than the preceding chambers. Aperture appears to be slit like or oval. This is the first ever report of this genus in Saudi Arabia.

SUBORDER VERNEUILININA Mikhalevich & Kaminski, 2004

Superfamily VERNEUILINACEA Cushman, 1911

Family Prolixoplectidae Loeblich & Tappan, 1985

Genus *Riyadhella Redmond*, 1965

Type species: *Riyadhella regularis* Redmond, 1965; (OD).

Remarks: *Riyadhella* is also reported from the Bajocian to Bathonian of Siberia (Azbel et al., 1991) but the wall of the Siberian specimens is non calcareous and therefore the Siberian species should be placed in a different genus.

Riyadhella arabica Redmond, 1965

(pl. 35, fig. b)

Riyadhella arabica REDMOND, 1965. p. 136, pl. 1, figs. 35. – BANNER et al., 1991, p. 132, fig. 66.

Remarks: Our specimens are very similar to the holotype illustrated by Banner et al., (1991). It is also reported from MFS J30 by Sharland et al., (2001), but it was not found by the author of this thesis in the same unit.

Riyadhella elongata Redmond, 1965

(pl. 5.11, figs. a-c)

Riyadhella elongata REDMOND, 1965, p. 136, pl. 1, figs. 20-21. -- DHUBAIB, 2010, p. 247, pl. 1, fig. 1-13.

Remarks: Small elongated species with parallel sides. Banner et al. (1991) gave an emended description of the species and I followed their species concept. Common in the studied section.

Riyadhella inflata Redmond, 1965

(pl. 5.1, figs. e-f, pl. 5.7, fig. a)

Riyadhella inflata REDMOND, 1965, p. 137, pl. 1, figs. 23-24. -- BANNER et al., 1991, p. 134, figs 67–68

Remarks: Banner et al. (1991) gave an emended description of the species and I followed their species concept. Redmond (1965) reported it as a common species in upper part of Dhruma Formation (D6) and is also found common in the studied section.

Riyadhella regularis Redmond, 1965

(pl. 5.9, figs. e-f, pl. 5.18, figs. c-d)

Riyadhella regularis REDMOND, 1965. p. 138, pl. 1, figs. 32-34. -- BANNER et al., 1991, p. 131, figs. 57–63. -- DHUBAIB, 2010, p. 247, pl. 1, fig. 1-13.

Remarks: Common in the studied section (D5). Banner et al. (1991) gave an emended description of the species and I followed their species concept.

SUBORDER ORBITOLININA Kaminski, 2004

Superfamily PFENDERINOIDEA Smout & Smugden, 1962

Family Pfenderinidae Smout and Sugden, 1962

Subfamily Pseudopfenderininae Septfontaine, 1988

Genus *Siphovalvulina* Septfontaine, 1988

Type species: *Siphovalvulina variabilis* Septfontaine, 1988, OD (M).

Siphovalvulina sp.

(pl. 5.5, fig. a, pl. 5.6, fig. b-c)

Remarks: Common in the studied sections. Small trochospiral conical forms with 3 chambers with various states of preservations.

Subfamily Paleopfenderininae Septfontaine, 1988

Genus *Steinekella* Redmond, 1964

Type species: *Steinekella steinekei* Redmond, 1964; OD

Steinekella steinekei Redmond, 1964

(pl. 5.7, fig. b)

Steinekella steinekei REDMOND, 1964. p. 259, pl. 2, figs. 8-14.

Remarks: Only single specimen of the species was found.

Subfamily Pfenderininae Smout & Smugden, 1962

Genus *Pfenderina* Redmond, 1964

Type species: *Pfenderina neocomiensis* Pfender, 1938

Pfenderina gracilis Redmond, 1964

(pl. 5.8, fig. b; pl. 5.18, fig. e)

Pfenderina gracilis REDMOND, 1964, p. 255, pl. 1, figs. 14-16.

Remarks: Common in the upper part of the studied section. Our specimens are in agreement with the illustrations of the types given by Redmond (1964).

Pfenderina inflata Redmond, 1964

(pl. 5.8, fig. a)

Pfenderina inflata REDMOND, 1964, p. 255, pl. 1, figs. 17-18.

Remarks: Common in the upper part of studied section. Our specimens are in agreement with the illustrations of the types given by Redmond (1964).

Subfamily Kurnubiinae Redmond, 1994

Genus *Kurnubia* Henson, 1948

Type species: *Kurnubia palastiniensis* Henson, 1948, p. 607, OD.

Kurnubia bramkampi Redmond, 1964

(pl. 5.14, fig. d)

Kurnubia bramkampi Redmond, 1964, p. 253, pl. 1, figs. 1-3.

Remarks: Our specimens are in agreement with the illustrations of the types given by Redmond, 1964.

Kurnubia variabilis Redmond, 1964

(pl. 5.14, fig. c)

Kurnubia variabilis Redmond, 1964, p. 254, pl. 1, figs. 5-8.

Remarks: Our specimens are in agreement with the illustrations of the types given by Redmond (1964).

SUBORDER TEXTULARIINA Delage & Herouard, 1896

Superfamily CHRYSALIDINACEA Neagu, 1968

Family Paravalvulinidae Banner, Simmons & Whittaker, 1991

Subfamily Paravalvulininae Banner, Simmons & Whittaker, 1991

Genus *Pseudomarssonella* Redmond, 1965

Type species: *Pseudomarssonella maxima* Redmond, 1965; OD.

Pseudomarssonella sp.

(pl. 5.16, fig. d)

Remarks: Very rare in study material. Test conical flairing and does not become parallel sided. Coiling trochospiral comprised of 5 -6 whorls with about 4 chambers in the final whorl. Wall finely agglutinated, aperture indistinct.

Genus *Redmondoides* Banner, Simmons & Whittaker, 1991

Type species: *Pseudomarssonella media* Redmond, 1965.

Redmondoides inflatus Redmond, 1965

(pl. 5.2, figs. a-e, pl. 5.10, figs c-f)

Redmondoides inflatus REDMOND, 1965, p. 134, pl. 1, figs 4-5.

Redmondoides inflatus (Redmond). -- BANNER et al., 1991, p. 120, figs. 38–39

Remarks: This species is more broadly conical than the others. Type specimens are from the D6 member of the Dhruma Formation.

Redmondoides lugeoni Septfontaine, 1977

(pl. 5.12, figs. a)

Valvulina lugeoni SEPTFONTAINE, 1977, p. 612, pl. 2, figs. 2-5.

Redmondoides lugeoni (SEPTFONTAINE).-- DHUBAIB, 2010, p. 247, pl. 1, fig. 1-13.

Remarks: Banner et al. (1991) gave an emended description of the species and give its geographical distribution. We followed their species concept.

Redmondoides media (Redmond, 1965)

(pl. 5.3, fig. a; pl. 5.4, figs. g-h)

Pseudomarssonella media REDMOND, 1965, p. 135, pl. 1, figs. 11-13**.**

Redmondoides medius (Redmond). -- – BANNER et al., 1991, p. 120, figs. 35–37. -- DHUBAIB, 2010, p. 247, pl. 1, fig. 1-13.

Remarks: Banner et al. (1991) gave an emended description of the species and we followed their species concept.

Redmondoides primitivus (Redmond, 1965)

(pl. 5.3, figs. c-d, pl. 5.4, figs. c-d)

Pseudomarssonella primitiva REDMOND, 1965, p. 136, pl. 1, figs. 16-18.

Redmondoides primitivus (Redmond). -- BANNER et al., 1991, p. 122, figs. 40–41. -- DHUBAIB, 2010, p. 247, pl. 1, fig. 1-13.

Redmondoides rotundatus (Redmond, 1965)

(pl. 51, fig. g, pl. 5.4, figs. e-f)

Riyadhella rotundata REDMOND, 1965, p. 140, pl. 1, figs. 36-39.

Redmondoides rotundatus (Redmond). -- – BANNER et al., 1991, p. 125, figs. 42–45, 79. --DHUBAIB, 2010, p. 247, pl. 1, fig. 1-13.

Remarks: *R. rotundatus* is characterized by its high chambers and convex apertural face. Our species are more coarsely agglutinated than other species of *Redmondoides*. Banner et al. (1991) gave an amended description of the species and we followed their species concept.

(For *redmondoides* sp., Juvinile and deformed specimens were named as sp.

Genus *Riyadhoides* Banner, Simmons & Whittaker, 1991

Type species: *Pseudomarssonella mcclurei* Redmond, 1965

Riyadhoides mcclurei (Redmond, 1965)

(pl. 5.19, figs. a-b, pl. 5.16, fig. i)

Pseudomarssonella mcclurei REDMOND, 1965, p. 135, pl. 1, figs 8–10.

Riyadhoides mcclurei (Redmond). -- BANNER et al., 1991, p. 129, figs. 55–56.

Remarks: Redmond (1964) reported it as less abundant in the upper part of Middle Dhruma Formation (D6). Our specimens are not as long as the type specimens described by Banner et al. (1991).

ORDER SPIRILLINIDA Gorbatchik and Mantsurova, 1980

SUBORDER INVOLUTINA Hohenegger and Piller, 1977

Superfamily INVOLUTINOIDEA Butschli, 1980

Family Involutinidae Butschli, 1980

Subfamily Aulotortinea Zaninetti, 1984

Genus *Andersenolina* Neagu, 1994

Type-species: *Andersenolina bancilai* Neagu, 1994; OD.

Andersenolina alpina (Leupold, 1936)

(pl. 5.15, fig. e)

Coscinodiscus alpinus LEUPOLD, 1936, p. 610, pl. 18, figs. 1-8.

Andersenolina alpina (Leupold). -- DHUBAIB, 2010, p. 247, pl. 1, fig. 1-13.

Remarks: Restricted to the upper part of our outcrop of the D5 member. Reported as common by Dubaib (2010) from the D6 member of the Dhruma Formation.

Andersenolina elongata (Leupold, 1936)

(pl. 5.15, fig. f)

Coscinoconus elongatus LEUPOLD, 1936, p. 617, pl. 18, figs. 12-14.

Andersenolina elongata (Leupold). -- DHUBAIB, 2010, p. 247, pl. 1, fig. 14-18.

Remarks: Restricted in the upper part of our outcrop of D5 member. Reported as common by Dubaib (2010) from the D6 member of the Dhruma Formation.

SUBORDER Spirillinina Hohenegger and Piller, 1975

Family Spirillinidae Reuss and Fritsch, 1861

Genus *Spirillina* Ehrenberg, 1843

Type species: *Spirillina vivipara* Ehrenberg, 1843

Spirillina polygyrata Guembel, 1862

(pl. 5.5, fig. f, pl. 5.16, fig c)

Spirillina polygyrata GÜMBEL, 1862, p. 214, pl. 4, fig. 11a–c. -- BLANK, 1990, p. 84, pl. 1, figs 3–4.

Remarks: Our specimens agreed well with illustrations given by Blank (1990) from southern Germany.

ORDER LAGENIDA Lankester, 1885

SUBORDER LAGENINA Delage and Herouard, 1896

Superfamily NODOSARIACEA Ehrenberg, 1838

Family Nodosariidae Ehrenberg, 1838

Subfamily Nodosariacea Ehrenberg, 1838

Genus *Nodosaria* Lamarck, 1812

Type species: *Nautilus radicula* Linne, 1758, p. 711; SD (SM).

Nodosaria fontinensis Terquem, 1870

(pl. 5.19, figs. c)

Nodosaria fontinensis TERQUEM, 1870, p. 353, pl. 26, fig. 1.

Nodosaria fontinensis Terquem, 1870. -- BLANK, 1990, p. 114, pl. 2, fig. 27

Remarks: Our specimens agreed well with illustrations given by Blank (1990) from southern Germany.

Nodosaria sp.

(pl. 12, figs. g-h)

Remarks: Broken and incomplete specimens were placed under *Nodosaria* sp.

Genus *Pseudonodosaria* Boomgaart, 1949

Pseudonodosaria hybrida (Terquem & Berthelin, 1875)

(pl. 5.1, fig. a)

Glandulina hybrida TERQUEM & BERTHELIN, 1875, p. 22, pl. 1, fig. 26

Pseudonodosaria hybrida (Turquem & Berthelin). -- CIFELLI, 1959, p. 318, pl. 5, figs 7–11

Remarks: We based our description on identification done by Cifelli, 1959.

Pseudonodosaria vulgata

Pseudonodosaria vulgata (Borneman, 1854)

(pl. 5.19, figs. e)

Glandulina vulgata BORNEMAN, 1854, p. 31, pl. 2, figs 1–2.

Pseudonodosaria vulgata (Borneman). -- CIFELLI, 1959, p. 318, pl. 5, fig. 3.

Remarks: We based our description on identification done by Cifelli, 1959.

Subfamily Lingulininae Ehrenberg, 1838

Genus *Lingulina* d'Orbigny, 1826

Type species: *Lingulina carinata* d'Orbigny, 1826

Lingulina sp.

(pl. 5.1, fig. b; pl. 5.11, fig. d)

Remarks: Specimen is small with parallel sides consisting of 6 chambers. Sutures between the last 3 chambers are shaped like an inverted V. Wall is very finely costae with at least 10 costae on each side. Very rare, only one specimen recovered.

Family Lenticulinidae Chapman, Parr & Collins, 1934

Subfamily Lenticulininae Chapman, Parr & Collins, 1934

Genus *Lenticulina* Lamarck, 1804

Type species: *Lenticulites rotulatus* Lamarck, 1804; SD.

Lenticulina spp.

(pl. 5.5, 5.7, fig. d; pl. 5.2, 5.11, 5.19, fig. f; pl. 5.13, fig. a-e)

Family Polymorphinidae d'Obrigny, 1839

Subfamily Polymorphininae d'Orbigny, 1839

Genus *Polymorphina* d'Orbigny, 1826

Type Species: *Polymorphina burdigalensis* d'Orbigny, 1826

Polymorphina sp.

(pl. 5.5, fig. e; pl. 5.8, fig. d; pl. 5.11, fig. g-h)

Remarks: We did not attempt to differentiate the species of *Polymorphina*.

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ACADMIC CREDENTIALS:

1. **M.S. Geology:**

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   Institute of Geology, University of the Punjab, Lahore, (2007 – 2012)

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PERSONAL EXPERIENCE:

Educational Projects Completed:

- **Silurian Project**: Worked on Silurian Qusaiba Shales (Most important Source rocks) in Qasim Area of Saudi Arabia for age diagnostic Graptolites & Microfossils. (*Funded By: National Science Technology and Innovation Plan of Saudi Arabia (NSTIP*)).
- **Jurassic Project**: Worked on Carbonate Jurassic Dhruma Formation (Important Reservoir) for Sedimentology, Sequence & Bio Stratigraphy of the formation exposed near Riyadh, Central Saudi Arabia. (*Funded By: National Science Technology and Innovation Plan of Saudi Arabia (NSTIP*)).
- **Miocene Project**: Worked on Carbonate Miocene Formations (Important Reservoirs) for Sedimentology, Biostratigraphy & Geochemistry exposed in the eastern region of Saudi Arabia. (*Funded By: Research Institute of KFUPM & ARAMCO).*

Field Works:

- Geological field trip to **Bornholm Island Denmark** to study the Green sands of upper Cretaceous Arnager Formation, lower Jurassic Sandstones and other strata exposed throughout the Island.
- Geological field trip near **Gubbio, Italy** to see the characteristics of Cretaceous-Tertiary (K-T) boundary exposed in the area.
- Geological Field Trip of Dinosaur Ridge, **Denver, USA** to see the Dinosaur foot imprints in Triassic rocks.
- Geological field trip to **Denmark & Sweden** (2 weeks) to see different formations with their diagnostic features and meet with the officials of Geological survey of Denmark & Greenland.
- Geological Field trip of **Oman** to see the strata exposed from Pre-Cambrian to Recent rocks along with the most complete succession of Ophiolites exposed in the country.
- Geological field trip to Rub-al-Khali desert (**The Empty Quarter**) for studying the migration and origin of Sand Dunes and their chronology.
- Geological field trips of all regions of **Saudi Arabia** in-order to understand all the rocks from Pre-Cambrian basements rocks to recent alluvial sands exposed throughout Saudi

Arabia. Major areas include igneous regions of Makkah, Harrats of Madinah, Cambrian to Permian Rocks of Northern Qasim region, Triassic to Cretaceous sequence of Riyadh region, Tertiary sequence of Easter Province and Sand deposits of Rub al Khali desert in Southern Saudi Arabia.

- Geological Mapping of Ramli Section Islamabad and Changla Gali section Hazara, Pakistan.
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- Won **Gold Medal** in **Imperial Barrel Award** (IBA) of **American Association of Petroleum Geology** (AAPG) for **Middle East Region**. (March, 2015)
- Won **Stoneley Medal** in **Imperial Barrel Award** (IBA) of **American Association of Petroleum Geology** (AAPG) **Global** held in Denver, USA. (June, 2015)
- Secured fully funded scholarship from "**Ministry of Higher Education of Saudi Arabia**" for Masters studies in King Fahd University of Petroleum & Minerals, Dhahran Saudi Arabia.
- Selected as a delegate and participated in a tour of **Youth Parliament Pakistan** to Stockholm, Sweden organized by the Swedish Institute. (December, 2012).
- 146-149 score in GRE

PUBLICATIONS:

- **Conference Publications:**
  - A shallow-water Ammobaculoides assemblage from the Middle Jurassic (Bajocian) Lower Dhruma Formation of Central Saudi Arabia. *By Michael A. KAMINSKI and **Muhammad Hammad MALIK***
    (Presented in: 16th Czech-Slovak-Polish Paleontological Conference and 10th Polish Micropalaeontological Workshop, Krakow, Poland).
  - Sedimentological and Petrographic studies of D4, D5 and Lower D6 Members of Middle Jurassic Carbonate Dhruma Formation, NW Riyadh, Saudi Arabia. *By **Muhammad Hammad MALIK***
    (Presented in: Geo 2016, Bahrain).

- **Journal Publications:**
    - Optimization of the Acetic Acid method for microfossil extraction from lithified carbonate rocks: Examples from Middle Jurassic Dhruma Formation and Middle Miocene Dam Formation in Saudi Arabia. *By Septriandi A. Chan,* ***Muhammad H. Malik****, Michael A. Kaminski, Lamidi O. Babalola.*
      (Journal: Arabian Journal of GeoSciences)
    - A shallow-water Ammobaculoides assemblage from the Middle Jurassic (Bajocian) Lower Dhruma Formation of Central Saudi Arabia. *By Michael A. KAMINSKI and* ***Muhammad Hammad MALIK***
      (Journal: Micropaleontology)
    - High resolution stratigraphic architecture and sedimentological heterogeneity of D4, D5 and Lower D6 Members of Middle Jurassic Carbonate Dhruma Formation, NW Riyadh, Saudi Arabia. *By* ***Muhammad Hammad MALIK,*** *Dr. Khalid Al-Ramadan and Michael. A. Kaminski.*
      (In writing)

MEMBERSHIPS:

- Member of AAPG & Vice-President of AAPG-KFUPM Chapter
- Member EAGE, SEG, DGS and PAPG

WORKSHOPS/SEMINARS ATTENDED:

- **Attended 3 weeks long course on Foraminifera in International School of Foraminifera (ISF), Urbino, Italy. (June, 2014)**
- **Attended 2 days long workshop on "Core Studies" organized by Saudi Aramco**
- **Attending 1-day workshop on "Basin Modeling" organized by Saudi Aramco**
- Participated in One Day Seminar on "Hazards of Geography: Earthquakes, Floods and Landslides".
  (Course Instructor: Dr. Dave Patley Director, Institute of Hazard Risk and Resilience, University of Durham, U.K)
- Organized and Participated in a Week Long Workshop on "TECTONICS OF PAKISTAN" with Distinction. (Resource Person: Dr Abdur Rauf Nizami)
- Participated in One Day Technical Talk on "Roll of The Chamman Transform Boundary Fault on Deformation of the Eastern Kharan Fore Arc Basin". (Organized By PAPG-PU Chapter)
- Organized and Participated in a Technical Talk on "Tectonics: An Exploration Tool".
  (Resource Person: Dr Abdur Rauf Nizami)

- Organized and Participated in a Seminar on “Exploration of natural Resources: Environmental Issues and research”. (Resource Person: Dr Tariq Cheema, Syncrude Canada Ltd, Alberta, Canada)
- Participated in a One Day Study Tour on “Understanding the Nature of MBT, Nathia Gali Fault and Stratigraphic variations at K-T Boundary”. (Organized by PAPG)

INTEREST/HOBBIES:

- Photography, Travel Blogging, Traveling, Hiking, Reading books,
- Swimming, Rowing (**Member University Rowing Team**).
- Internet Surfing, Current affairs, Football and Basketball (**Member Departmental Basketball Team**).
- Physical Fitness.